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Dowel Bar Retrofit Mix Design and Specification

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DOWEL BAR RETROFIT MIX DESIGN AND SPECIFICATION

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16. Abstract

The focus of this project was on identifying critical properties that control long-term performance of repair concrete, especially rapid-setting materials extended using pea gravel (maximum size aggregate 9.5 mm).

In the first phase of this project, four commercial rapid-setting materials (CRSMs) were selected and development of mixture proportions in terms of optimum pea gravel content and water content was performed. Optimized mixtures were further evaluated at three different initial temperature conditions. The properties evaluated included workability, setting time, rate of compressive strength developed, slant shear bond strength, freeze-thaw resistance, air-void system characteristics of hardened concrete, drying shrinkage and cracking potential. It was observed that some of the CRSMs evaluated did not meet requirements of ASTM C 928. All, except one, CRSMs tested exhibited low resistance to freezing and thawing but all had high resistance to cracking.

In the second phase of the project, rapid-setting self-consolidating concrete (RSSCC) was developed using ternary blend of cementitious materials, high-range water reducer (HRWR) and accelerators. Slump flow, visual stability index (VSI), compressive strength at various ages and the power consumption values for the mortar mixer indicated that a five minutes mixing sequence involving a 2-Step addition of HRWR produces stable RSSCC mixture. The results of various tests carried out indicate that it is possible to develop a small aggregate size-based self-consolidating repair concrete that achieves a compressive strength of 19 MPa at the end of 6 hrs, has good bond characteristics and excellent freezing and thawing durability (DF>90%).

The sensitivity of RSSCC to aggregate characteristics and production variables was also evaluated. Specifically, the influence of aggregate gradation and aggregate moisture content using different types of mixers and re-mixing after a period of rest was evaluated. It was observed that variation in aggregate moisture content and aggregate gradation resulted in noticeable changes in fresh concrete properties such as the slump flow, stability and V-funnel flow values. While changes in moisture content and gradation of aggregates had an impact on the early (6 h) compressive strength, the compressive strength at the end of 24 hours was not significantly affected.

17. Key Words dowel bars, rapid setting repair materials, self-consolidating concrete, durability	**18. Distribution Statement** No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

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Dowel Bar Retrofit Mix Design and Specification

EXECUTIVE SUMMARY

INTRODUCTION

Current INDOT specifications for repair materials to be used in dowel bar retrofit (DBR) applications (Sections 507.08 and 901.07 of INDOT's Book of Specifications) are based, in large part, on the requirements of ASTM C 928 and the manufacturer-provided technical performance data. The objective of this research was to develop a set of performance specifications for patching materials that can be used in dowel bar retrofit repair applications in the state of Indiana.

To accomplish this goal, five commercial rapid-setting repair materials and one custom-developed rapid-setting, self-consolidating concrete were extensively evaluated for different performance characteristics. In addition, the assessment of the influence of production variables on properties of these materials was also conducted. The project was broadly divided in to two phases. Phase I consisted of studies of commercial rapid-setting repair materials and Phase II consisted of development of rapid-setting, self-consolidating concrete (RSSCC).

Phase I was divided into two primary steps. Step 1 involved selection of five commercial rapid-setting repair materials based on compilation of published reports on the performance of existing DBR installations and a list of commercial rapid-setting materials (CRSM) approved for use by different state departments of transportation (DOTs). Optimal mixture proportions for the selected CRSMs were developed using slump flow and the rate of compressive strength development as the criterion. In Step 2, the effect of temperature of mixture ingredients at the time of placement on early age and long-term properties of the selected mixtures were studied. The fresh and hardened concrete properties studied were slump flow, setting time, rate of compressive strength development, slant shear bond strength, cracking potential, freeze-thaw resistance and air-content of hardened concrete.

Phase II was also divided in to two steps. Step 1 involved development of optimal mixture proportions for RSSCC. The focus of Step 2 was on evaluation of robustness of RSSCC to variation in production parameters, such as moisture content of aggregates (for two water-to-cementitious ratios and two types of mixing equipment), aggregate gradation, and the effect of remixing after a period of rest.

FINDINGS

Due to small dimensions of the DBR slot, it was found (by using a mock up) that CRSMs used in this research required the largest amount of extra water to be added to facilitate placement. The measurement of the slump flow instead of the slump gave a good indication of the flowability of the repair concrete, and thus its placeability. The cracking potential of all CRSMs tested in this research was low. All but one CRSM exhibited low resistance to freezing and thawing cycles. When compared to the requirements traditionally used for plain concrete to achieve adequate freeze-thaw resistance, the spacing factor and specific surface values for hardened CRSMs were out of range.

The early-age and long-term performance of CRSMs were found to be affected by the temperature of materials at the time of casting and the ambient temperature at which the repair concrete was cured. All but one CRSM reached the stipulated compressive strength as stated in ASTM C 928 for material temperature condition of 23°C. A similar observation was also be made for material and curing temperature of 40°C. The final setting time and the rate of compressive strength development was low for repair concrete cast with materials at 10°C and cured at the same temperature.

The research conclusively proved that small repair jobs can be successfully completed using RSSCC. The mixing sequence and total mixing time are important factors for achieving a stable RSSCC. A two-step procedure for addition of superplasticizers implemented in the research was found to be beneficial for achieving stable and cohesive RSSCC.

The final RSSCC mixture consisted of a ternary blend of Type III Portland cement, silica fume, and micro-fine fly ash. The total cementitious materials content of this mix was 560 kg/m3 and it required 2.15% of HRWR (by weight of cement) and accelerator dosage of 8.8% (by weight of cement) at water-to-cementitious ratio of 0.31.

The moisture content of aggregates at the time of mixing was found to have played an important role in the robustness of RSSCC. Mixtures having w/cm of 0.36 were more robust and less sensitive to variations in aggregate moisture conditions than those made with w/cm of 0.31.

IMPLEMENTATION

Based on the observed performance of various CRSMs studied in this project it is recommended that the current INDOT specifications and guidelines for repair materials for use in load transfer restoration applications be revised. The summary of main reasons for this recommendation is briefly listed below.

Experimental results showed that the performance criteria currently laid down in the INDOT standards fall short with respect to specifying the following key parameters that influence the durability of the repaired systems:

1) Measurement of workability (in terms of flowability) of the repair concrete
2) Measurement of compressive strength at early ages
3) Measurement of freeze-thaw durability
4) Determination of cracking susceptibility
5) Performance criteria for placement of repair concrete at extreme temperatures (10°C and 40°C)

To achieve stable rsscc for small batch volumes (1–2 cu. Ft.) It is essential that the mixing sequence and mixing time be strictly adhered to. The trial mix procedure should be prepared before the start of the project to optimize the aggregate content and the superplasticizer dosage.

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CHAPTER 1 INTRODUCTION

1.1 Background

Many jointed concrete pavements (JCP) have been constructed without mechanical load transfer devices across joints and some of them experience significant faulting as a result of poor load transfer (Gulden and Brown, 1986; Nantung and Olek, 2002; Porter and Guinn, 2002; FHWA April 98). In some cases, significant faulting was also observed in concrete pavements that were originally constructed with dowel bars but in which dowels lost their functionality under heavy traffic loading. In order to increase the life of in-service concrete pavements that exhibit poor load transfer, highway agencies have begun to use various devices to restore joint or crack load transfer to an acceptable levels, to prevent further faulting, spalling, and to reduce the deflection and pumping. Generally, load transfer devices such as retrofitted dowel bars, double V-shear devices, figure-eight devices, and miniature I-beam devices are adopted for load transfer restoration (Gulden and Brown, 1986; Pierce, 1994; Embacher, 2001).

Dowel-bar retrofitting (DBR) is a technique used successfully by several states to address faulting in older jointed plain concrete pavements (Pierce, 1994; Nantung and Olek, 2002). The typical approach is to saw cut and jackhammer out the slots for the dowels and to place the dowels in the slots. The dowels are placed on chairs and the slots are then backfilled with a rapid setting concrete mixture. The repaired area of the pavement is then diamond-ground to restore smoothness.

The DBR technique as a preventive maintenance option for cracked concrete pavement has been introduced in Indiana with various degree of success. In many cases, although the placing procedures have been performed correctly, the quality of the concrete grout material itself was questionable (Eacker, 1999). In a recent study by the Michigan Department of Transportation, it was found that the problem was typically related to the variability of repair concrete, lack of air entrainment and poor freeze-thaw resistance. Although Indiana and Michigan Departments of Transportations (DOT's) share common retrofit procedures, Indiana uses different approved mix designs and materials. In view of the reported problems related to the quality of the repair concrete, and to ensure consistent performance of the dowel bar retrofit installations, the mixture design parameters and composition needs to be investigated (Nantung and Olek, 2002).

1.2 Objective and Scope

The overall goal of this research project was to analyze in detail commonly used commercial rapid-setting materials (CRSMs) used specifically for repair in DBR projects and to develop a new, rapid-setting repair material which will overcome the fallibilities of the CRSMs, if any. The scope of the research can be summarized as follows:

1) Develop criteria for selection of a few most common commercial rapid-setting materials currently available in the market for laboratory studies.

2) Establish key performance requirements for rapid-setting materials used in DBR applications.
3) Develop optimum mixture proportions for all selected CRSMs for a desired level of flow and highest possible compressive strength at various ages.
4) Evaluate early age and long term behavior of CRSMs at three possible site temperature conditions. Assess fresh and hardened properties, including rate of compressive strength development, bond strength, cracking potential and resistance to freeze-thaw of CRSM pre-conditioned to different initial temperatures selected to represent a range of expected field temperatures during DBR installation.
5) Develop rapid-setting self-consolidating concrete (RSSCC) which would meet the key performance requirements using locally available materials and onsite mix production methods.
6) Evaluate in details the stability and sensitivity of RSSCC to variation in production parameters such as changes in aggregate moisture content, aggregate gradation and remixing after a period of rest.

1.3 Research Approach

To meet the goals and objectives described above, an extensive research plan was developed. The plan was divided into two distinctive phases: 1) Phase I- Study of commercial rapid-setting materials and 2) Phase II- Development of rapid-setting self-consolidating concrete.

Phase I consisted of performing an extensive review of literature and various state DOTs specifications in order to choose four commercial rapid-setting materials typically used for concrete repair. The materials chosen had different chemical compositions and were predominantly either alumina based cements or magnesium phosphate-based components. The chosen materials were then analyzed extensively to determine their early age and long term performance characteristics as a function of initial temperature conditions.

Phase II consisted of methodically developing mixture proportions for RSSCC by optimizing the quantities of different ingredients such as Type- III cement, silica fume, micro-fine flyash, high range water reducer (HRWR), set accelerator and water to cementitious ratio (w/cm). This phase also involved the identification of the mixing sequence suitable for preparation of RSSCC. In addition, an extensive experimental program was also carried out to examine the stability and robustness of RSSCC to variations that are likely to occur on a repair job site.

1.4 Organization of the Report

The work performed during this research has been divided into seven chapters. Chapter 1 provides background information on the research objectives and scope of this work. The literature review presented in Chapter 2 contains a summary of the published reports and papers on various aspects of performance of dowel bar retrofit projects. It also contains a review on self-consolidating concrete (SCC) in terms of its mixture design principles, techniques for assessment of flowability and filling ability, and sensitivity of SCC to production variables.

Chapter 3 outlines the experimental procedures adopted to carry out the research objectives. The materials used, along with the description of the test methods and adopted performance requirements are also presented in detail in this chapter. Chapter 4 presents the analysis of the test results of different commercial rapid setting materials. Chapter 5 discusses the results of the different stages adopted for optimizing the mixture proportions of RSSCC. The effects of different mixing techniques, type of mixing equipment and the influence of characteristics of cement, fine aggregate, silica fume, micro-fine fly ash, and chemical admixtures are also described. The sensitivity of RSSCC to different production variables forms the core of Chapter 6. Chapter 7 provides an overall summary of this work, including conclusion and recommendations for further research.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

The focus of the literature review task of this project was to critically evaluate the dowel bar retrofitting (DBR) materials and practices used by various state agencies to improve load transfer efficiency of faulted or cracked concrete pavements.

Section 2.2 of this review deals with the mechanisms and measurement techniques of load transfer in concrete pavements. The criteria for load transfer restoration as developed by FHWA are also analyzed in this section. Dowel bar retrofitting technique is one of the prevalent methods adopted by Departments of Transportation (DOT) for improving the load transfer capabilities of concrete pavements.

The standard design and construction methodology for DBR techniques adopted by different DOTs is reviewed in detail in section 2.3. This section also contains an exhaustive survey on the parameters that determine the performance of DBR system.

Self-compacting concrete (SCC) is a new type of high performance concrete characterized by its ability to flow under its own weight and achieve good consolidation without any mechanical vibration. These attributes of SCC make it an ideal candidate for DBR applications. The basic properties of SCC along with materials and production parameters that influence its performance have been evaluated in section 2.4. In particular, the sensitivity of SCC to production variables such as variation in mixing equipment, mixing sequence, mixing time, material variations in terms of aggregate gradations an aggregate moisture content have been discussed at length.

Section 2.5 is the concluding section of this chapter. It summarizes the findings of the literature review and discussed the gaps observed in the published literature for development of specifications for DBR techniques.

2.2 Load Transferring Capacity and Faulting of Rigid Pavements

Load transfer is the ability of a joint to transfer a portion of an applied load from one side of the joint to the other. The main criteria for evaluating the performance of the load transfer device, or for determining the need for restoration, is based on the amount of load transfer occurring between the loaded side and the unloaded side of the pavement slab. The ability to transfer load from one side of the joint or crack to the other is referred to as the load transfer efficiency (LTE). It is a major factor in the structural performance of the joint or crack. LTE could be defined quantitatively in terms of relative deflections across a joint or crack under loading, and is expressed in percents.

The amount of load transfer can be calculated by a method first used by Teller and Sutherland (1986):

$$LTE\% = [(2D_u)/(D_l + D_u)] * 100 \qquad (1)$$

where, LTE = Load transfer efficiency (%),

D_u = deflection of unloaded slab, and

D_l = deflection of loaded slab.

This equation is also been suggested by AASHTO and the American Concrete Pavement Association (ACPA) (Porter and Guinn, 2002) for expressing load transfer efficiency.

Joint efficiency (JE) is another parameter that is also used to describe the amount of discontinuity caused by a joint and is defined as follows:

$$JE\ (\%) = (D_u/(D_l)\ {*}100 \qquad (2)$$

Another measure of joint effectiveness is given by the following equation (Porter and Guinn, 2002):

$$LTE\ (\%) = (P_t/P_w){*}100 \qquad (3)$$

where, LTE = transferred load efficiency (%)

P_t = load transferred across the joint (lb)

P_w = applied wheel load (lb)

Faulting is one of the primary factors affecting the ride quality of rigid pavements. Faulting is the difference of slab elevation across a joint or a crack. Typically, the approach slab is higher than the leaving slab. Faulting can occur at transverse cracks as well as at transverse joints. Faulting can be caused in part by a buildup of loose materials under the approach slab near the joint or crack and by a loss of base material causing a depression under the leave slab. It can also be caused by the movement of the material out from under the leave slab and onto the pavement surface (Glauz *et al.*, 2002). The second mechanism is typically associated with wet conditions in the supporting structure and pumping action of the slabs caused by traffic, particularly heavy traffic.

2.2.1 Load-Transfer Mechanism

The load transfer efficiency in a given pavement can be achieved by several means, the main of which are briefly discussed below:

- Aggregate interlock between the slabs (across the joint or crack)

Transverse joints are created in new pavements by cutting the concrete only to the depth of about 1/3 of the thickness of the surface. This cut initiates a controlled crack that propagates downward through the concrete. The irregularity of the crack promotes aggregate interlock and load transfer at the joint. Aggregate interlock is the mechanical locking which forms between the fractured surfaces along the crack below the joint saw cut.

- Load transfer through the base material

Pavements are many times placed on top of a stabilized base and the stabilized base is placed over a subgrade material. Load transfer occurs through the subgrade. Stabilized bases reduce joint deflection, and improve and maintain load transfer under repetitive loads. This is the weakest means of obtaining load transfer since environmental conditions can rapidly reduce the load transfer efficiency.

- Load transfer devices

In jointed reinforced concrete pavements (JRCP), load transfer devices such as dowel bars are provided at the time of construction itself to reduce faulting and transverse cracking.

2.2.2 Need for Load-Transfer Restoration

Most jointed plain concrete pavement (JPCP) designs which do not incorporate dowel bars and are subjected to medium and high volumes of heavy trucks will, over time, lose some of the load transfer ability (Gulden and Brown, 1986). Jointed reinforced concrete pavements (JRCP) may also develop mid-panel transverse cracks due to rupture under repeated heavy truck loading or corrosion of the reinforcing steel (FHWA, April 98). FHWA suggests the following guidelines for determining the need for load transfer restoration of jointed concrete pavements:

- Faulting of individual joints or cracks of 3 mm or more; and/or
- Deflection load transfer of less than 70 percent; and/or
- Differential deflection between approach (loaded slab) and leave slab (unloaded slab) of over 0.25 mm (0.01 in.); and /or
- Cumulative faulting of joints and cracks over 500 mm/km.

2.3 Overview of Dowel-Bar Retrofit Technology

Improved techniques for retrofitting of existing concrete pavements with dowel bars have been developed over the past decade by several agencies, including several state DOTs. Dowel bar retrofitting consists of sawing slots for the dowels across transverse joints, inserting the dowels, and grouting them in place. This is followed by grinding to remove faulting and smoothing the grout surface where the dowels were installed. The load transfer across the joint provided by the dowel bars significantly slows the development of new faulting under truck traffic. Dowel bar retrofit is not appropriate if the concrete slabs have multiple cracks or if there are other significant durability problems with pavement such as alkali-silica reaction (ASR), sulfate attack, D-cracking, blow outs or punch outs (Embacher, 2001; Gulden and Brown, 1986; Pierce, 1994).

2.3.1 Procedures for Dowel Bar Installation

Generally, a number of dowel bars are installed across the joint in the inner wheel as well as the outer wheel paths (Embacher, 2001; Gulden and Brown, 1986; Pierce, 1994). The installation of the dowel bars is typically performed according to the procedure as described in the following paragraphs. Slots, about 2.5 in. wide are cut parallel to the centerline, using saw with diamond tipped blades; and with length and depth adequate for the dowel bar to be positioned at mid-depth of the pavement and centered over the transverse crack. The slot depth is controlled by the thickness of the slab (Embacher, 2001). Jackhammers are used to chip out the concrete between the saw cuts. To prevent damage to part of the pavement that will not be removed any jack hammers used to break loose the concrete have a weight less than 30 lb. The slots are then cleaned out with a chipping hammer to allow the dowel bar assembly to sit parallel to the pavement surface. All exposed surfaces and cracks in the slot are sandblasted and cleaned of cutting debris. The transverse crack at the bottom of the slot is then caulked to prevent any of the grout material from entering the joint. The slots are cleaned out with a gas powered blower just prior to placing the dowel bar assembly into the slot. All the slot surfaces are coated with a bonding agent generally comprising of a cement and water slurry.

The dowel bar assemblies are prepared by placing compressible spacers on each of the dowel bars and fitting the end caps. It is necessary to ensure that the expansion caps are tight fitting and made of non-metallic material which will allow 6 mm (¼ in.) movement at each end of the dowel. State DOTs specify that the dowel bar must be coated with a thin layer of oil or any other bond breaking material just prior to installation in the slot. Two chairs are used to firmly hold the dowel bar in the slot during the placement of the patching material. The width of the chairs should be equivalent to width of the slot and a minimum of @ ½ inch clearance between the bottom of the dowel and bottom of the slot should be provided.

Figure 2.1 shows a typical dowel bar placement details. The magnitude of the distances marked as A, B, C, D and E in Figure 2.1 have been enumerated for different state DOTs in Table 2.1. Figure 2.2 and Figure 2.3 show the standard drawings for the dowel bar retrofit system adopted by the Indiana DOT. As seen in Figure 2.2, the diameter of the dowel bar used on INDOT projects should be based on the thickness of the pavement. Table 2.1 summarizes the dowel bar configurations, diameter of the dowel bar and the board filler thickness adopted by various state DOTs. Most DOTs have adopted a configuration of three dowel bars in the inner and the outer wheel paths. The distance between two dowel bars (denoted by "B" in Figure 2.1) is generally about 300 mm, whereas the distance of the first dowel bar from the centerline (denoted by "A" in

Figure 2.1) varies between 600 mm to 762 mm. The length of saw cut is generally variable and depends on the specific site conditions. As a rule of thumb, the length of the saw cut should be sufficient to align the dowel bars correctly. The dowel bars are aligned across a joint or a crack in such a way that equal length of dowel bar is present on either side of the joint or crack. Most state DOTs specify the width of the saw cut to be about nearly 1.9 to 1.95 times the diameter of the dowel bar. The diameter of the dowel bar adopted by all the state DOTs is 38 mm, whereas the length of the dowel bar varies between 450 mm to 457 mm.

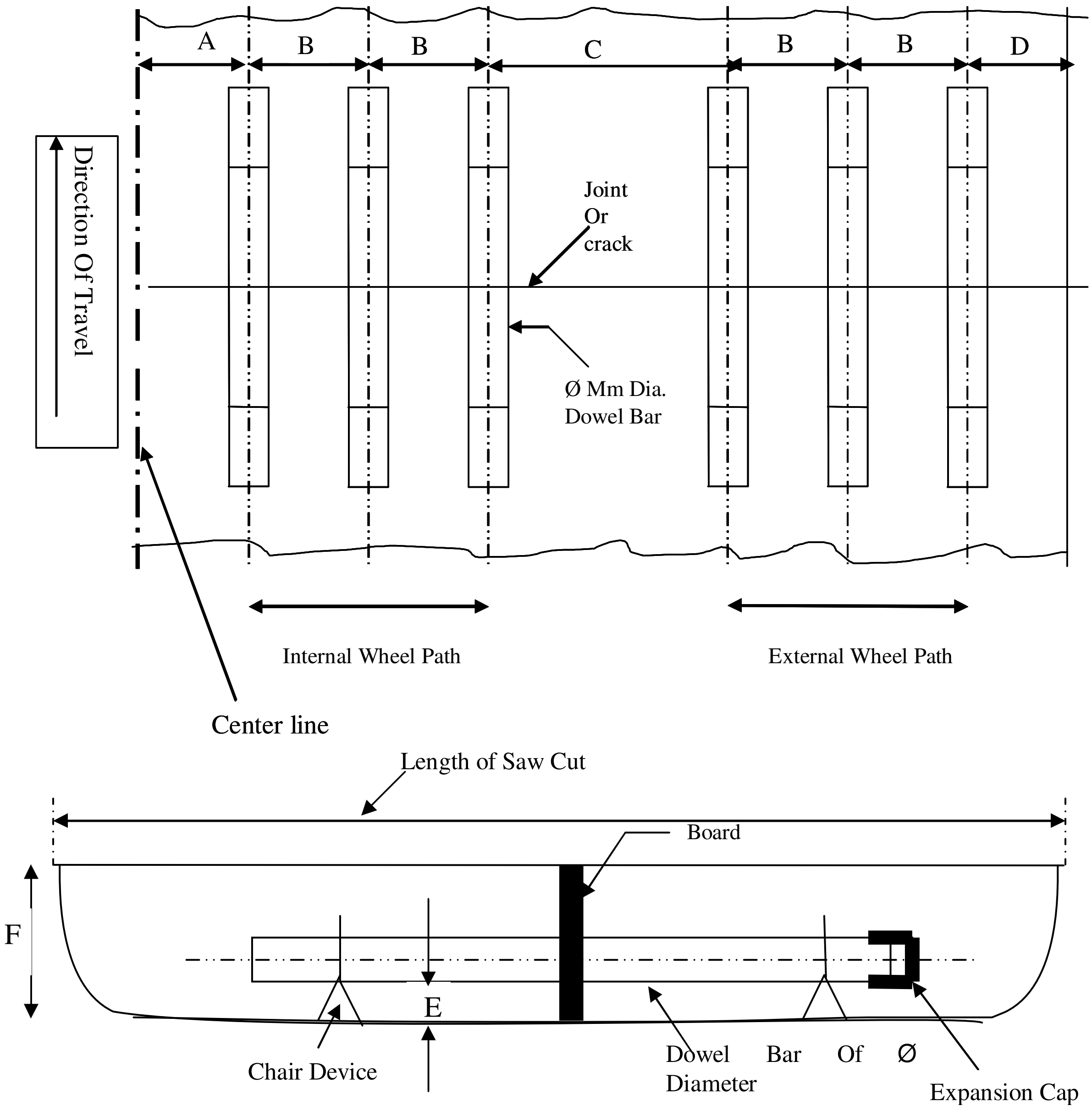


Figure 2.1 Dowel bar placement details

Note :

- Refer to Table 2.11 for details
- Figure not to scale

Table 2.1 Comparison of dowel bar configurations and dowel bar designs for different state DOTs.
(All measurements in mm. Refer to Figure 2.1 for definition of distances.)

No.	State	A	B	C	D	E	F	Diameter of dowel bar	Board filler thickness	Length of dowel bar	Length of saw cut[a]	Width of saw cut	Dowel bars [b]
1)	Wisconsin	600	300	1500		12		38	6	450 ± 3		64	3
2)	California (San Diego County)		305	305		13		38	6	457		64	4
3)	Washington	610	305	305		13	146	38	6		560[c]	63	3
4)	Minnesota	600	300			13	Mid slab depth	37.5	variable	475		65	3
6)	Nebraska	762	305	1220	458	12.5	Mid slab depth	38	7	457		63.5	3
7)	Ohio					12.5		38		460		65	3
8)	Kansas	600	300	1500	300	12	Mid slab depth	38	12	450±3	900[c]	65	3
9)	Indiana	610	305	305	305	12.5	Mid slab depth	38		457		64	

Note: a. Length of saw cut is as per requirement unless and otherwise stated

b. Dowel bars placed in each wheel path unless and other wise stated

c. Also depends on crack dimensions

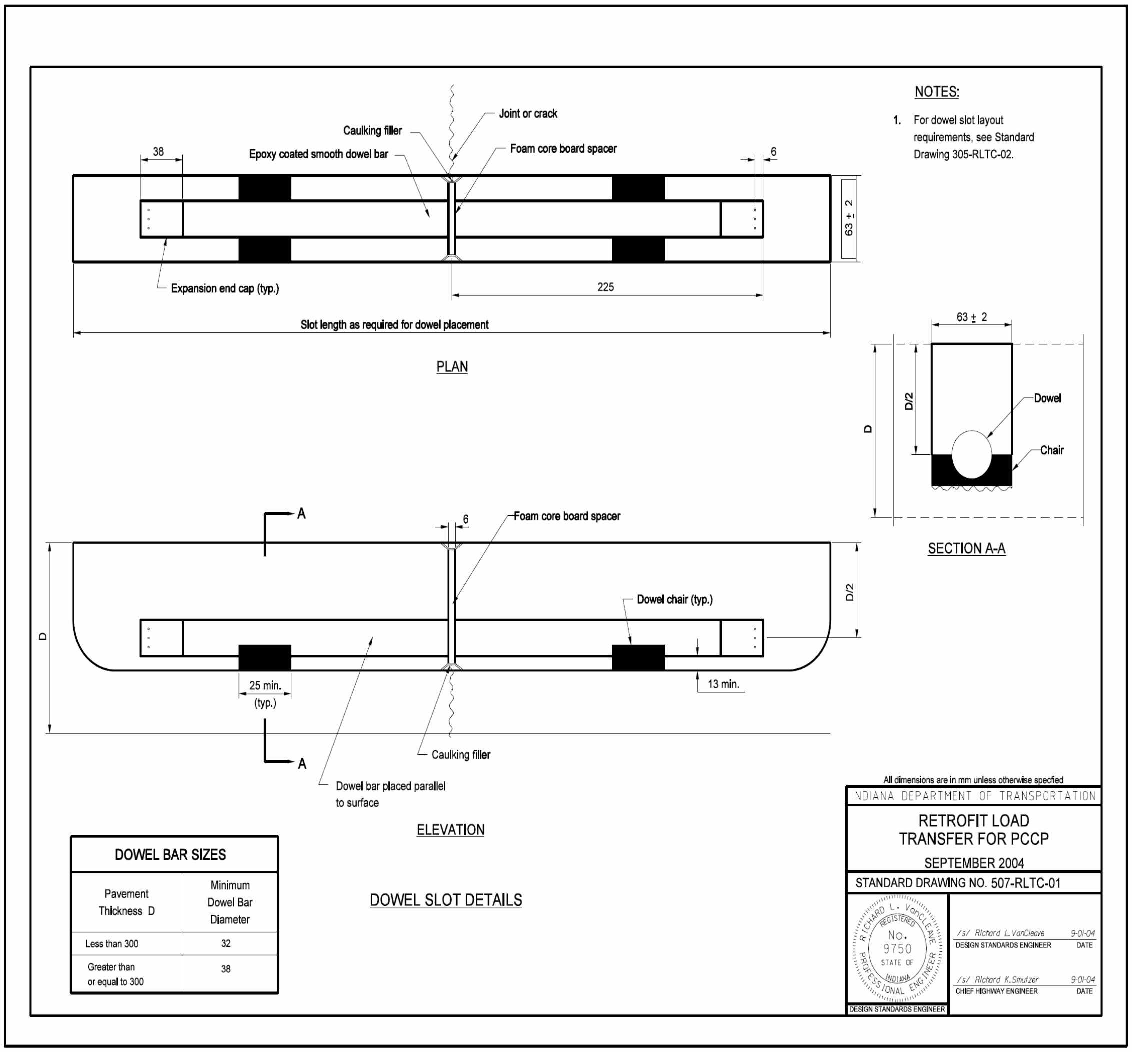
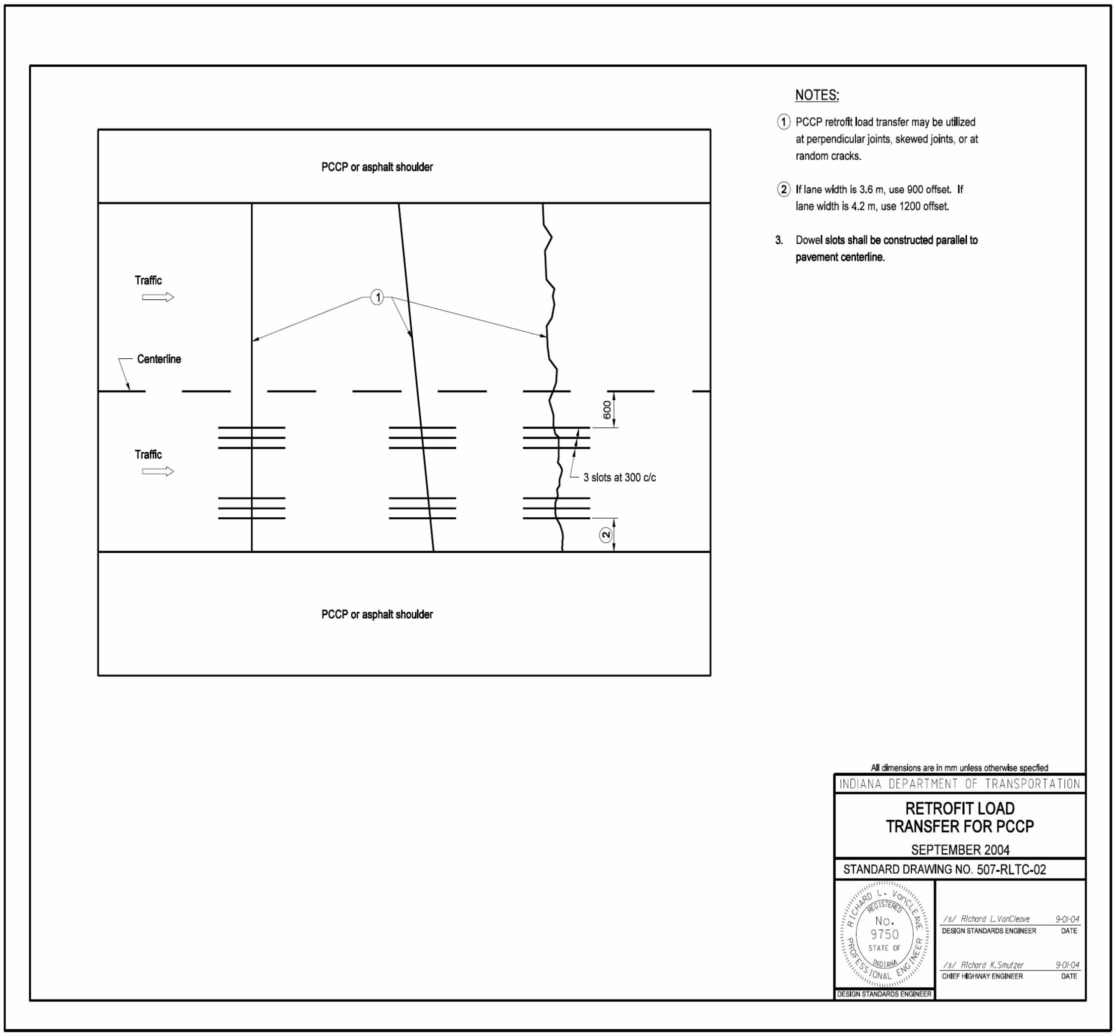


Figure 2.2 Standard dowel bar installation of INDOT



NOTES:

① PCCP retrofit load transfer may be utilized at perpendicular joints, skewed joints, or at random cracks.

② If lane width is 3.6 m, use 900 offset. If lane width is 4.2 m, use 1200 offset.

3. Dowel slots shall be constructed parallel to pavement centerline.

All dimensions are in mm unless otherwise specfied

INDIANA DEPARTMENT OF TRANSPORTATION

RETROFIT LOAD
TRANSFER FOR PCCP
SEPTEMBER 2004

STANDARD DRAWING NO. 507-RLTC-02

RICHARD L. VanCLEAVE REGISTERED No. 9750 STATE OF INDIANA PROFESSIONAL ENGINEER

DESIGN STANDARDS ENGINEER

/s/ Richard L.VanCleave 9-01-04
DESIGN STANDARDS ENGINEER DATE

/s/ Richard K.Smutzer 9-01-04
CHIEF HIGHWAY ENGINEER DATE

Figure 2.3 Standard layout of dowel bar across a crack/joint as per INDOT

The spacer material (board) that is placed in the middle of the dowel bar assembly (as shown in Figure 2.1) should be capable of remaining in a vertical position and be in contact with all edges of the slot. Once the dowel assembly is in-place, the grout or patching material is placed around the dowel and consolidated using a hand-held needle vibrator. The surface of the slot is then finished flush with the pavement surface and sprayed with a curing compound. Upon completion of the installation of the dowel bars, the entire concrete surface is diamond ground to remove any faulting. Figure 2.4 illustrates a completed dowel bar retrofit across a crack (Wilson and Toepel, 2002).

Figure 2.4 Dowel bar retrofit across a crack (Wilson and Toepel, 2002)

It is essential to determine the load transfer efficiency of the joint after dowel bar retrofitting is completed. Properly installed dowel bars should increase the LTE to 90-100 percent when tested after a curing period of few days (FHWA, April 98). LTE measurements should be taken periodically and a record should be maintained to evaluate the long term performance of the pavement.

The primary objective of this study is to develop mix design and specifications for dowel bar retrofit for the Indiana Department of Transportation (INDOT). DBR specifications from several states have been reviewed and the findings were used to refine the work plan proposed for this study. Among the data collected during this review, was information on the type of patching materials commonly specified for DBR projects. The summary of this information from select DOTs is given Table 2.2.

Table 2.2 List of approved patching materials of selected state DOTs

Patch Material	State									
	South Dakota	South Carolina	Ohio	Nebraska	Minnesota	Michigan	Indiana	Kansas	New York	Georgia
Patchroc 10-60	*	*	*			*				
Five Star Highway Patch	*	*	*	*	*	*		*	*	*
L&M Durapatch Highway	*	*		*		*				
Set 45	Not Allowed					*	*		*	
Burke 928 Fast Patch		*	*	*		*				
High Performance Repair Mortar				*						
Thorac 10-60 Rapid Mortar						*	*			*
Highway DB Retrofit Mortar				*	*			*	*	
Speed Crete 2028					*			*	*	*
CTS Rapid Set Dot		*	*	*					*	

10-60 Rapid Mortar Emaco T 430				*						
Pavepatch Concentrate DBM				*						
Speed Crete Greenline					*					*
Chem Speed Greenline					*					
HD-50						*				
HD-Dot Patch						*				
Mono Patch							*			
Thorac 10-61							*			*
Duracal Normal Weather							*			
Duracal Hot Weather							*			

Analysis of these data indicate that Five Star Highway Patch™ has been approved by all DOTs reviewed for this project. Some other repair materials that are approved by many of the DOTs include are Patchroc 10-60™, L & M Durapatch Highway™, Highway Dowel Bar Retrofit Mortar™, SET-45™, ThoRoc 10-60 Rapid Mortar™, Speed Crete 2028™, etc.

As an example of properties that may be specified for DBR materials, Table 2.3 provides a summary of specification for three selected states (S. Dakota, New York and California). An extensive, 10-year study by Washington DOT (WSDOT) resulted in a set of specific requirements that are summarized in Table 2.4 (Pierce *et al.*, 2003). Most of the DOTs included in Table 2.3 and 2.4 specify that the compressive strength of the material (as per test method ASTM C-109) should be minimum 35 MPa at 28 days. The maximum allowable shrinkage values range from 0.13% at 4 days for South Dakota DOT to 0.4% expansion for NYDOT. New York state DOTs have specified that the patching material should withstand 50 cycles of freeze thaw with a maximum loss of 6%; whereas, WSDOT specifies that the scaling resistance at 25 cycles of freezing and thawing should be 1 lb/ft^2 maximum (using the ASTM C-672 test method).

In contrast to the previously mentioned states, Indiana DOT does not have specific requirements for materials to be used in DBR. Rather, it allows for DBR installation to be constructed using a general specification for rapid setting patch materials (see Table 2.5).

Table 2.3 Comparison of selected DOT specification requirements

	Test	**State**		
		South Dakota	**New York**	**California**
Mortar	**Compressive Strength (psi)**	at 3 h 3000 psi (20.7 MPa) minimum	at 1 h 2610 psi (18 MPa) minimum	at 3 h 3045 psi (21 MPa) minimum
		24 h min 5000 psi (34.47 MPa)	at 24 h 3645 psi (25 MPa)	at 24 h 5000 psi (35 MPa) minimum
			at 28 days 5000psi (35 MPa)	
	Final Set Time	at minimum of 25 minutes	minimum of 5 minutes at 24±1° C	
	Shrinkage/ Length Change	at 4 days -0.13% maximum	expansion of no more than 0.4% and contraction no more than 0.05%	
With Maximum Aggregate Extension	**Flexural Strength**	at 24 h 500 psi (3.4 MPa)		at 24 h 510 psi (3.5 MPa) minimum
	Bond to Dry PCC	at 24 h 400 psi (2.75 MPa)	Minimum of 217 psi (1.5 MPa) after 24 hrs[1]	304 psi (2.1 MPa) minimum[1]
	Bond to SSD PCC	24 h 300 psi (2.6 MPa)		406 ps (2.8 MPa) minimum[1]
	Other details	Contractor shall verify the results of the suppliers mix design before start of work.	ability to withstand 50 cycles of freeze thaw (10% NaCl soln) with a maximum loss of 6%, workable mixture when extended with a minimum 60% CA 1 aggregate by weight of rapid setting material	Water Absorption 10% maximum, Drying Shrinkage at 4 days 4%, Soluble Chlorides by Mass % -0.05 maximum, Soluble Sulfates by mass %-0.25%

Table 2.4 Patching material requirements adopted by WSDOT (Pierce *et al.*, 2003)

Property	Test Method	Requirement
Mortar		
Compressive strength		
At 3 hours	ASTM C 109	Minimum 3,000 psi
At 24 hours	ASTM C 109	Minimum 5,000 psi
Length change		
At 28 days	ASTM C 157	0.15 Percent maximum
Total Chloride Ion Content	ASTM C 1218	1 lb/yd^3 maximum
Bond Strength		
At 24 hours	ASTM C-882 (Modified by ASTM C-928)	Minimum 1,000 psi
Scaling Resistance		
At 25 freeze-thaw cycles	ASTM C-672	1 lb/ft^2 maximum
Concrete		
Compressive strength		
At 3 hours	ASTM C 39	Minimum 3,000 psi
At 24 hours	ASTM C 39	Minimum 5,000 psi
Length change		
At 28 days	ASTM C 157	0.15 Percent maximum
Bond Strength		
At 24 hours	ASTM C882	Minimum 1,000 psi

Table 2.5 INDOT specifications for patching materials

Physical Test	Test Method	Requirement
Setting Time	ASTM C 266	
Normal weather		
Initial at 22ºC (72ºF)		10 - 20 minutes
Final at 22ºC (72ºF)		12 - 35 minutes
Hot weather		
Initial at 35ºC (95ºF)		10 - 20 minutes
Final at 35ºC (95ºF)		12 - 35 minutes
Compressive strength, minimum	ASTM T 109	22ºC (72F), normal
1 h		14 MPa (2000 psi)
2 h		21 MPa (3000 psi)
24 h		34.5 MPa (5000 psi)
28 days		55 MPa (8000 psi)
Compressive strength, minimum	ASTM C 109	35ºC (95ºF), hot
3 h		21 MPa (3000 psi)
24 h		34.5 MPa (5000 psi)
28 days		55 MPa (8000 psi)
Relative dynamic modulus	ASTM C 666	
Procedure B 300 cycles		95% minimum
Slant shear bond strength, minimum	ASTM C 882	
28 days		17 MPa (2500 psi)
Flexural strength, 24 h	ASTM C 78	
Mortar only		3.5 MPa (500 psi)
Mortar - Aggregate extension		4.0 MPa (600 psi)
Shrinkage, maximum	ASTM C 157	
28 days		0.03%
Scaling resistance	ASTM C 157	
5 cycles		0 rating, no scaling
25 cycles		0 rating, no scaling
50+ cycles		1.5 rating, light scaling

Note: Current INDOT specifications cover patching materials in general, and are not specifically designed for patching materials used for dowel bar retrofit projects.

2.3.2 Effectiveness of Dowel-Bar Retrofit Techniques

Many state DOTs have carried out research to study the effect of different dowel configurations, type of rapid setting patching materials, diameter of dowel bar and dowel bar lengths on load transfer efficiency and durability of the retrofitted pavement (Embacher, 2001; Embacher, and Snyder, 1999; Embacher, *et al.*, 1999; Hall *et al.*, 1993; Mamlouk, *et al.*, 2000; Rettner and Snyder, 2001). Most of the researchers concluded that for the success or failure of the complete DBR system depends on the dowel bar device, the patching material used and the construction practices adopted (Embacher,2001; Embacher, and Snyder, 1999; Embacher, *et al.*, 1999; FHWA, 1998; Hall, Darter, and Armaghani, 1993; Mamlouk, *et al.*, 2000; Pierce,1994; Porter and Guinn, 2002; Rettner and Snyder, 2001; Wilson and Toepel, 2002).

2.3.2.1 Influence of Configuration of the Dowel Bars

Gulden and Brown (1986) recommend installation of three dowel bars in the outer wheel path and two dowel bars in the inner wheel path. However, they also indicated that before opting for removal of dowel bars from the inner wheel path, the long term performance data should be first obtained for a given dowel bar configuration .

Florida DOT (Embacher, and Snyder, 1999; Mamlouk, *et al.,*2000) installed different configurations of dowel bars in 0.8 km section of I-10 and observed their performance over a period of 5 years. A significant finding from that study was that larger diameter (38 mm (1.5 in.)) dowels were more effective in reducing faulting in comparison to 25-mm (1.0 in.) dowels. In all but few cases, sections with five dowel bars per wheel path had slightly higher load transfer efficiencies than sections with three dowel bars per wheel path. The study also indicated that dowel length does not appear to have any significant effect on load transfer efficiency. Study was carried out by installing dowel bars of length 356 mm (14 in.) and 457 mm (18 in.). In 1993, Washington State DOT changed the dowel bar configuration from four dowel bars to three dowel bars per wheel path based on a study carried out by Florida DOT (Eacker, 1999).

Minnesota DOT (MnDOT) (Eacker, 1999; Embacher, and Snyder, 1999; Embacher, *et al.*,1999; Rettner and Snyder, 2001) has carried out extensive studies on the effectiveness of dowel bar retrofit with the variations in dowel bar length, diameter and configurations. It was generally observed that the length of dowel bar or the number of dowel bars did not affect the performance in terms of load transfer to a large extent (Eacker, 1999).

MnDOT (Embacher, *et al.*, 1999; Rettner and Snyder, 2001) studied the influence of the length of dowel bars by comparing the performance of 380 mm (14.9 in.) long to that of 457 mm (17.9 in.) long dowel bars. The results indicate that the sections with the shorter bars lost on average about 1.4% LTE, while the sections with the 457 mm long dowel bars gained about 0.4% LTE during the same period. This indicates that shorter bars are sufficient to provide adequate load transfer, if placed properly. Reduced lengths would lead to smaller slots, thus resulting in lower cost of cutting and reduced amounts of patching material requirement. Hence, shorter bars would lead to overall cost savings. Also, the bid price for shorter bars was almost 6% lower than the bid for longer dowel bars ($33.00 each vs. $ 35.00 each) on this project. It was recommended that further study on the effects of dowel length should be performed (Embacher, *et al.*, 1999).

In another study performed by MnDOT (Rettner and Snyder, 2001), five test sections with different dowel configurations were installed on US 52 near Zumbrota, Minnesota. These configurations included:

- three dowel bars only in the outer wheel path in the right lane,
- three dowel bars in the outer wheel path and two in the inner wheel path in the right lane,
- three dowel bars in both wheel paths in the right lane,
- three dowel bars in the outer wheel path and two in the inner wheel path in both lanes, and
- three dowel bars in both wheel paths in both lanes.

No difference in the load transfer efficiency and faulting measured in the right wheel path of the right lane relative to any of the dowel patterns used was observed.

Retrofitting of the failing pavement was carried out on the Minnesota Trunk Highway 23 located between Ogilive and Mora (Embacher, 2001). The study was divided into three different sections, one dealing with evaluation of the patching material (to be discussed in section 2.3.2.2), one dealing with the evaluation of the influence of the length of the dowel bar, and one dealing with evaluation of the role of the configuration. MnDOT compared the performance of 325 mm long dowel bars to 375 mm long dowel bars. Significant difference in the load transfer efficiency was not observed for the two lengths over a period of two years. Another test section of the study was carried out to compare the performance of retrofit bars in just the outer wheel path versus both the inner and outer wheel paths. This was done by using various configurations of dowels in the wheel paths. These configurations included using three dowel bars in the inner and outer wheel paths, three dowels in only the outer wheel path, and using three dowel bars in the outer wheel path and two in the inner path wheel path only. Different configurations did not significantly change the values of LTE.

Michigan DOT (Mamlouk, *et al.*, 2000) carried out a study to determine the effect of depth of placement of the dowel bars on the performance of retrofitted pavements. Dowel bars were placed at mid depth of the slab (at 140 mm (5.5 in.)) and at shallow depth of 100 mm (4in.) along I-75 in Monroe County. There were no significant differences between the performances of sections with mid depth and shallow depth dowels.

2.3.2.2 Influence of Patch Materials and Construction Practices

The role of patching material used to seal the dowel bar in the slots is of prime importance in the dowel bar retrofit technique. The patching material must develop sufficient strength and bond to allow the dowel bar to open and close and to withstand the vertical stresses imparted by the loads (Gulden and Brown, 1986). The dowel bar must be able to accommodate horizontal joint movements without damaging the bond between the patching material and the pavement. The patching materials must have little or no shrinkage during curing, since shrinkage of the patching material can cause weakening or failure of the bond with the existing concrete. The patching material must develop strength rapidly, so that traffic can be allowed on the slabs in a reasonable length of time (3 to 4 hours) (Nantung and Olek, 2002).

The material selected for patching purposes should be based on parameters such as cost, ease of use, and time required for opening the road to traffic (Embacher, *et al.*, 1999; Hall, *et al.*, 1993). The LTE and differential deflection values are greatly improved if the patching material has high initial strength gain (Embacher, *et al.*, 1999). In one of the earliest published studies (Gulden and Brown, 1986) have strongly stressed the importance of the type of patching material to be used for DBR applications. They suggest various laboratory tests that should be conducted on new materials to determine ultimate bond strength, rate of strength gain, working time, and other factors before any material can be used on a DBR project.

The Wisconsin study (Wilson and Toepel, 2002) concluded that air content of proprietary mortar mixes cannot be used as a quality control parameter for monitoring patching mixes as most proprietary materials used for DBR works are high alumina cement based products which may or may not conform to normal concrete evaluation parameters .

It is essential that patching material used attains the desired compressive strength within a specified time limit (FHWA, 1998). Non achievement of strength due to cold weather conditions can lead to cracking of patching material. Retrofit dowels were used by INDOT in I-70 west bound ramp and I-465 south bound on the eastside of Indianapolis. Different kind of patching materials such as Set 45, Rapid Set, 9-bag

Portland cement, mortar with latex modifier or 2% $CaCl_2$ were used in this study (FHWA, 1998). It was observed that 9-bag Portland cement (P.C.), type I mortar with latex modifier and 2% $CaCl_2$ had severely cracked. It was observed that Set 45 patches were generally intact with only a reflective crack across the original pavement crack. Subsequent lab work indicated that the 9-bag P.C. type I mortar might not have achieved 100 psi cube compressive strengths in cold weather within six hours of mixing.

Freeze thaw durability of patching materials is considerably reduced if the patching material is extended to at about 80 to 100% (Eacker, 1999; Wilson and Toepel, 2002). Higher amount of aggregates leads to less paste volume in the mixture, and weaker material. It was observed by MnDOT (Eacker, 1999) that 100% extension of patching material lead to higher water demands, since dry aggregate tend to absorb the mix water. A study was initiated by Wisconsin DOT (Wilson and Toepel, 2002) in February 2001 to investigate early distress for a one hundred lane miles of dowel bar retrofit project constructed from 1999-2000 on I-39 in central Wisconsin. Three different types of patching material were used: 1) ThoRoc 10-60C at 80% extension, 2) Five Star Highway Patch, and 3) Dayton/Superior RDB mortar. A significant portion of the DBR work was experiencing early distress in the form of deterioration of the mortar material in the dowel bar slots. The report concludes that the primary cause of distress appears to be lack of freeze thaw durability of proprietary mortar mixes. The freeze thaw loss was observed to be particularly high (in some cases nearly 100%) for core samples containing mortar with 80 to 100% extension. The distress (or deterioration) of the mortar was observed to be starting at the joint and working its way out in a series of concentric arcs growing deeper and widening out from the joint as the deterioration advanced. Various areas also exhibited scaling of the patching material surface, with surface loss of approximately 1/16 in. - 1/18in. The primary distress appeared to be causing secondary distress in the form of spalling of original concrete adjacent to the slots.

The water content of the patching material should be carefully controlled in order to reduce the probability of shrinkage cracks and debonding of patching material from the original pavement (Rettner and Snyder, 2001). MnDOT used a state developed patching material (3U18) and a proprietary material for DBR project. It was detected that both materials suffered bond and void problems. It was concluded that extraordinary effort should be made to insure that all faces of the removal area are thoroughly cleaned and abraded to assure the best possible bond between the patching material and the pavement (Embacher, and Snyder, 1999; Rettner and Snyder, 2001).

A few State DOTs have reported cracking in the vicinity of dowel bars (Embacher, 2001; Hall, *et al.*, 1993; Pierce, 1994; Pierce, *et al.*, 2003). Dowel lock-up was observed to be a primary cause for of failure at a DBR project on Interstate 10 near Tallahassee, Florida (Hall, *et al.*, 1993). Many cracks were observed, spaced an inch or more apart, across the dowel slot, parallel to the transverse joint. The initial survey conducted in 1988 (two years after installation) indicated that the dowel and shear devices exhibited very little distress and that the major distress affecting the DBR installation were multiple hairline cracks in the dowel backfill. Between 1988 and 1991 the retrofit dowel bar developed considerable distress. At many locations, a series of horizontal cracks was observed between the dowel slots, parallel to the joint. Many cracks ran along the side of a dowel slot, and from there extended in to the slab.

When dowel bars are locked-up, joints are prevented from opening in response to falling temperatures. This causes high tensile stresses in the patching material and the surrounding concrete slab (Hall, *et al.*, 1993). Dowel lock-up may also be caused by development of bond between the patching material and the epoxy-coated dowels. It was suggested by the authors that since no bond breaker was used, a relatively strong bond could have developed between the epoxy coated dowel bars and the high strength patching material (HD-50 supplied by Dayton Superior) used. Dowel bar misalignment also played a part in locking-up the transverse joints according to these investigators. Another hypothesis presented was that high tensile stresses could have developed from a combination of heavy traffic loads, curling at the corners, and the presence of either voids or a non-uniform and stiff grout beneath the slab corners.

The first factor for assuming dowel lock-up as a reason for failure is the high frequency of cracking at dowel installations in both wheel paths. This suggests that whatever was causing the cracking is acting across the full slab width, and not just at the outer slab edge. If the cracking was caused by corner deflections or non uniform supports, the cracking would have been largely confined to the outer wheel path. The second factor is the low temperatures during construction. During low ambient temperatures, the joints were open wider when the dowels were installed and the low tensile stresses were induced in the backfill and slabs by further contraction during the months with more low temperatures.

WSDOT observed several instances of 45-degree cracking on an eight-kilometer section of DBR pavement (Pierce, *et al.*,2003). Based on the investigation of the cracking, two main causes were proposed as being responsible for the problem:

- dowel bars were placed below the mid depth of the slab.
- Cracking at the bottom of the dowel bar slot due to higher depth of slot and use of heavy jackhammer for slot cutting.

Debonding of patching material from the original pavement and development of longitudinal cracking in the newly installed patch was observed at many locations by WSDOT due to pre-existing longitudinal cracking. To eliminate this distress, WSDOT recommends either aligning the slots to miss any existing longitudinal cracks or by not placing a dowel bar in such locations.

The condition of sealant is also a major contributing factor to the distress of the repair mortar and in most cases partial sealant systems exhibit the most distress (Glauz *et al.*, 2002; Wilson and Toepel, 2002). The partially sealed joints tend to trap water and do not allow it to escape or evaporate, thus contributing to freeze thaw distress.

Proper construction practices, including proper alignment of the slots with the crack or joint, and proper placing of foam boards, dowel bar and the chair in the slot play an important role in the success of DBR repair and in improving the life of the pavement (Eacker, 1999; Glauz *et al.*, 2001; Glauz, *et al.*, 2002; Mamlouk, *et al.*, 2000; Pierce, *et al.*, 2003). Large amount of distress, including complete spalling of patching material, leading to exposure of the dowel bar was observed in many projects due to improper placing of dowel, and improper placing and consolidation of the patching material (Embacher, and Snyder, 1999; Embacher, *et al.*, 1999; Glauz, *et al.*, 2001; Pierce, *et al.*, 2003). Poor workmanship can lead to large scale failures of the dowel bar retrofit technique (Embacher, and Snyder, M. B., 1999; Glauz, D, *et al.*, 2001, 2002; Pierce, *et al.*, 2003). The effect of poor consolidation of the patching material on LTE and differential displacement values is much larger than the effect of any relatively small changes in the design of the dowel bar, for example, the length of dowel bar. Usage of proper mixers, which would mix the mortar materials consistently, is essential (FHWA, 1998).

INDOT has had a good experience with SET 45 as a patch material versus the P.C. with additives as patch material (FHWA, 1998). It has been observed that the presetting of dowel bars for alignment and subsequent placement of patching material gave rise to the possibility of voids under the bars. About one third of the 89% installations exhibited minor spalling along the majority of the pavement track.

Improper foam placement in San Diego County and in a few project of WSDOT has lead to formation of new transverse cracks and spalling of concrete (Pierce, *et al.*, 2003). The foam board was cut too short to span the entire width of the slot and caused spalling at the contact between the new and old concrete pavement due to thermal expansion. Heavy jack hammers should not be employed to cut the slots as they cause fracture in the existing concrete below the slots (Glauz, Smith and Alarcon, 2001, 2002).

2.4 Self-Consolidating Concrete

As discussed in the Chapter 1 of this report, one component of the scope of this study was to develop rapid setting, self-compacting concrete for DBR applications. To achieve this goal it is essential to study the effect of different powders that can be used to develop self-consolidating concrete (SCC) and the type of superplasticizers that can be used to achieve flowability. It is difficult to quantify the flowability and the stability of SCC by the conventional slump cone test conducted as per ASTM C 143 and other test methods need to be reviewed to test the flowability of SCC.

Self-consolidating concrete was first developed in 1988 in Japan in order to reduce honeycombing due to inadequate consolidation and vibration, thus paving way for durable concrete structures. Since then, investigations have been carried out and SCC has been used successfully in many structures, especially in areas with congested reinforcement. SCC can be defined as a highly flowable concrete that can spread into place under its own weight, and without segregation and bleeding (Okamura, and Ouchi, 1999). It can also be termed as "self-compacting concrete". The main reasons for the utilization of self-consolidating concrete can be summarized as follows (Chan and Chern, 2001; Hughes *et al.*, 2002; Lessard *et al.*, 2002; Okamura, *et al.*, 2000; Walraven, 2002):

(1) To shorten construction period,

(2) To ensure proper compaction of concrete, especially in areas congested with reinforcement where mechanical means of vibration are difficult,

(3) To reduce noise pollution due to vibration and

(4) To reduce cost of skilled workers and expensive vibrating equipments.

The flowability and the durability of SCC is achieved primarily by using various types of fillers i.e., flyash, limestone powder and chemical admixtures i.e. superplasticizers and viscosity modifying agents. Generally, the self compactability of a mix is sensitive to small variations in the characteristics of the components, such as the type and age of the cement, the type of sand and fillers (shape, surface, and grading) and the moisture content of the sand (Okamura, *et al.*, 2000). The fresh concrete properties are largely measured in terms of the slump flow and flow time. The mixes are investigated with a slump cone to determine the slump flow diameter and a V-funnel to determine the time the mixture needs to leave the funnel through the opening at the bottom. The slump flow helps in determining the stability of the mix in terms of segregation and bleeding, whereas the flow time determined with the help of V-funnel indicates the viscosity of the mix.

2.4.1 Need for Development of Rapid Setting Self-Consolidating Concrete (RSSCC)

Application of self-consolidating concrete as a repair or retrofitting material is also gaining momentum. In Netherlands (Walraven, 2002), the first large scale application of SCC was the retrofitting of the National Theatre in Hague. SCC was adopted to achieve uniform smooth finish which included tiny horizontal 8-mm ribs spaced at uniform distance. SCC with high flowability (flow diameter 730 mm) and low V-funnel time (8 - 9 seconds) was applied. Khayat and others (Khayat and Morin, 2002) have applied SCC for repair of parapet wall in Montreal. According to the authors, the motives for adopting SCC were threefold:

- reduction in noise levels due to location of structure in heavily traveled boulevard,
- restricted access to the bottom of the wall due to its bell shape and heavy reinforcement, and
- requirement of special surface definitions by the architect.

In Sheffield, U. K. (O'Flaherty and Mangat, 1999) laboratory testing and field applications on a highway bridge of self-consolidating repair materials was carried out. Three commercially available repair materials and one specially designed self-compacting concrete was used in the study. It was observed that the free shrinkage at 100 days of specially designed SCC samples stored at 20ºC and 55% RH for 24 hours after casting was the lowest. The setting time of the repair materials has not been specified by the authors, but since demolding time has been mentioned as 24 hours, it is assumed that the setting time of self-consolidating repair materials was similar to that of normal concrete, i.e., 6 - 10 hours.

Development of RSSCC has been included in the scope of this project due to the self-consolidation and flowability of SCC. Due to the small distance between the bottom of the dowel bar and the bottom of the slot (see Figure 2.1) commercial rapid setting material (RSM) are unable to flow underneath the dowel bar. It is perceived that the problem of voids underneath the dowel bars will be overcome with the use of RSSCC, which will fulfill the demand of filling ability, passing ability and segregation resistance.

2.4.2 Constituent Materials

Self-compactability refers to the ability of fresh concrete to deform and undergo change in shape and pass through obstacle under its own weight without exhibiting segregation, thus ensuring proper filling and high performance. Deformability of concrete is generally achieved by limiting the volume of coarse aggregate to reduce the inter-particles collision and the flow resistance. On the other hand, the resistance to segregation is controlled by the viscosity of the matrix of cement mortar (Yahia, A., *et al.*, 1999). Adequate resistance to segregation is achieved by reducing the water-to-cementitious materials ratio, increasing the cohesiveness of the paste by adding finer particles or using a viscosity-enhancing agent. To achieve self compactability, Okamura and Ozawa have suggested the following methods (Okamura H., *et al.*, 2000):

- limited aggregate content,
- low water-powder ratio, and
- use of superplasticizer

The role of fine powders and chemical admixtures (as discussed in the section 2.4.2.1 and 2.4.2.2) is very important in the development of SCC.

2.4.2.1. Fine powders in SCC

Fine powders in SCC include both cement and filler materials that are either pozzolanic or non pozzolanic. Among pozzolanic powders that can be added to the mix to achieve self compactability and cohesiveness are fly ash, micro fine fly ash (MFA), silica fume. Among non-pozzolanic powders/fillers limestone powder and dolomite fines are frequently used in SCC mixes. The fineness of these powders is typically preferred to be more than that of the cement adopted for the SCC mix. Figure 2.5 shows a graphical plot of fine powders versus the water/powder adopted by researchers in some of the published literature. Although the total powder content though is scattered between 315 kg/m^3 to about 900 kg/m^3, it can be observed that most of the data points lie within about 380 kg/m^3 to 600 kg/m^3.

Silica fume is effective in improving the workability of SCC and enhance its strength, but it requires a large dosage of superplasticizers (Obla *et al.*, 2003; Takada *et al.*, 1999; Wu-Fang *et al.*, 1999). Researchers have found that at a given workability and water content, concrete containing MFA could be produced at half the dosage of high range water reducers as compared to that of silica fume (Obla, *et al.*, 2003). The demand for superplasticizers (SP) increases as the percentage of silica fume in SCC is increased. Researchers, Wu Fang *et al*; (1999), have attributed the non performance of silica fume in SCC (in terms of decreased fluidity), to its fineness and low density. According to them, silica fume is easily absorbed on the surface of other particles and aggregates and if the water binder ratio is low, the mixtures can easily form flocculating structures.

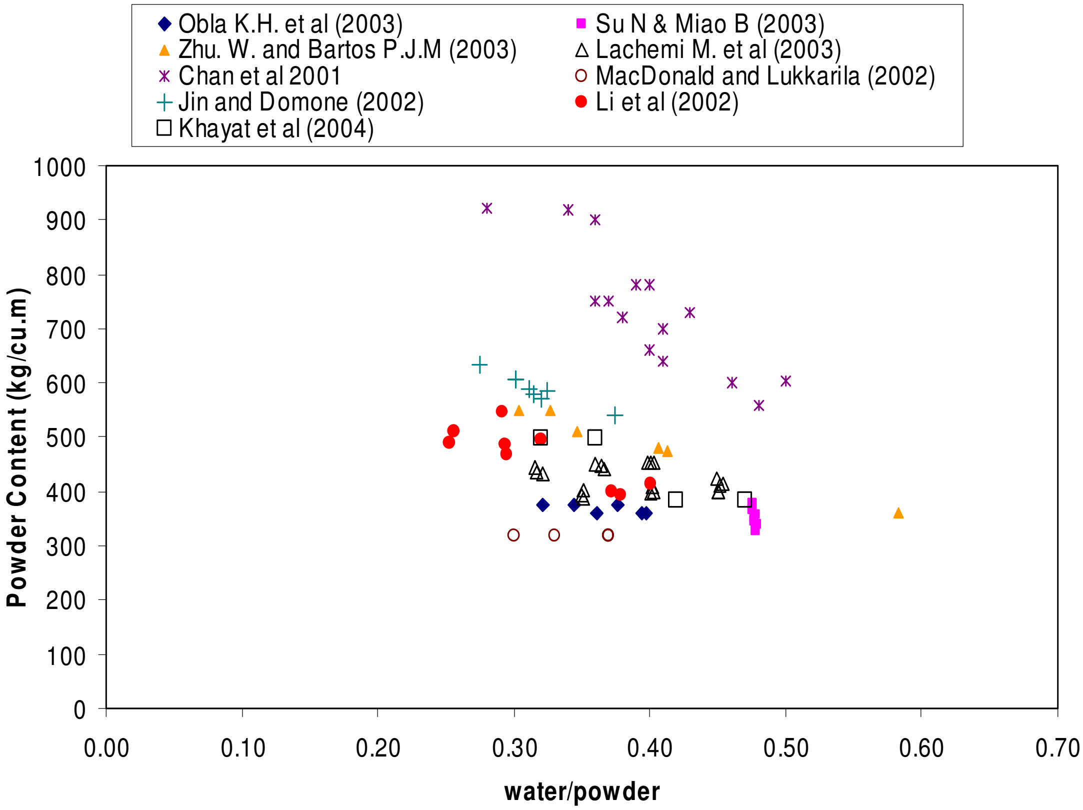


Figure 2.5 Powder content versus water/powder ratio

Use of fly ash or MFA can increase workability and stability of SCC mixture by virtue of their spherical shape and smooth surface (Shadle and Somerville, 2002; Wu-Fang, *et al.*, 1999). In addition to improved plastic and hardened properties, there are also economic and environmental benefits when fly ash or MFA are used in SCC.

If high early age compressive strength is required, use of fly ash in SCC is not beneficial due to its slow pozzolanic reactions at normal temperature (Obla, *et al.*, 2003; Wu-Fang, *et al.*,1999). However, use of ground fly ash or MFA instead of raw, unprocessed fly ash is very beneficial. According to Wu Fang *et al;* (Wu-Fang, *et al.*,

1999) slump flow of SCC containing ground fly ash was higher than that made with raw FA. Obla *et al*; (Obla, *et al.*, 2003) had a similar observation, wherein, they reported that concrete containing MFA had reduced water demand for a given slump as compared with the portland cement concrete. The same research also reported that MFA can be successfully used in place of silica fume to obtain high early age strength. They found that to reach the performance of silica fume concrete, at early age, MFA content must be slightly greater than the SF content, and that the total water content in the mixture needs to be reduced by about 10 percent as compared to that of silica fume concrete.

The addition of limestone filler (LF) to SCC helps in controlling segregation in the mix and in accelerating the hydration of clinker materials resulting in an improvement in early strength. The LF grains act as nucleation sites for CH and C-S-H reaction products at early hydration ages (Pera *et al.*, 1999).

2.4.2.2 Chemical Admixtures in SCC

Superplasticizer (SP) is one of the key components of self-consolidating concrete. However, one problem that has been pointed out regarding its usage in SCC, is the compatibility between cement and SP. In order to overcome this problem, the mechanism of interaction of cement and SP has been studied in detail by many researchers (Bonen and Sarkar, 1995; Hanchara and Yamada, 1999; Yoshioka *et al.*, 2002). The results of these studies provided information on the mechanism for both the fluidity just after mixing and the fluidity change with time and temperature as well as fluidity retention issues. The two types of SPs that are used to achieve high slump flow at low water to cementitious ratio are typically either poly-naphthalene sulfonate (NC) or polycarboxylate (PC) (Yamada, *et al.*, 2001). They have proposed that the performance of these SPs is described by two parameters, critical dosage and dispersing ability (Yamada, *et al.*, 2001).

It has been observed that the amount of PC adsorbed on cement hydrates depends on the sulfate ion concentration, and lower concentration is preferred for higher adsorption of PC (Yamada, *et al.*, 2001). Yamada and others (Yamada, Ogawa, and Takahashi, 2001; Yamamuro *et al.*, 2001), attempted to improve the compatibility between cement and SP by optimizing the chemical structure of PC. They were able to obtain a PC that is resistant to the variation of the sulfate ion concentration, by having longer main chain, longer side chain and higher ratio of carboxylic acid groups to the main chain length (COOH ratio) in the chemical structure of the PC. Some researchers, including Yamada, have proposed the blending of PCs with high adsorbing ability and low adsorbing ability to aid in balancing the high initial fluidity and the retention (Velten *et al.*, 2001; Yamada, *et al.,* 2001). A liquid admixture containing a polyether-based SP and polysaccharide derivative (NPD) as a viscosity agent was developed for SCC for the wall of LNG storage tank (Yamamuro, *et al.,* 2001). It was observed that by using a viscosity agent in the SP, the powder content could be reduced without sacrificing the self-compactability of the mix.

If fine powders like limestone are not used as fillers in the SCC, mixture then a viscosity modifying agent (VMA) is added during the mixing. VMAs are water-soluble polymers that increase the viscosity and cohesion of cement-based materials. The VMA aids in stabilizing the fluidity by preventing the occurrence of segregation or bleeding in the mix. A highly flowable concrete that does not possess sufficient viscosity can undergo segregation, especially as it flows between closely spaced obstacles such as reinforcing bars. This leads to blockages that can interfere with the filing of the congested section. According to Khayat, (1998) the cohesiveness of the concrete is related to the free water content in the mixture, which can be reduced by decreasing the w/c or by incorporating a VMA. Mixtures made with high paste content and a VMA exhibit less segregation and flow more readily around reinforcements than mixtures made with similar consistencies containing low water and high paste volumes and no VMAs. Figure 2.6 shows a graph of a study published by Khayat. It was observed that use of welan gum, a typical natural water soluble polysaccharide, reduced the maximum settlement and increases the filling ability of SCC as the dosage of VMA was increased from 0% to 0.05%. Rols *et al*; (1999) carried out a study on the effect of VMAs on the slump flow, segregation and rate of bleeding in SCC mixes by using three different types of viscosity agents.

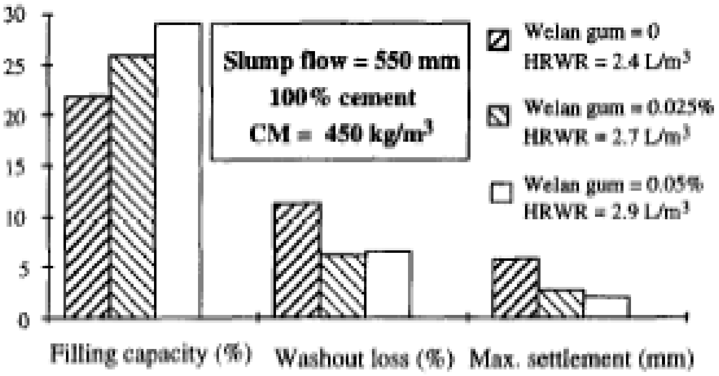


Figure 2.6 Effect of welan gum content on properties of SCC (Khayat, K. H., 1998)

The VMAs adopted were starch, precipitated silica, and a by-product from the starch industry. It was observed that starch and precipitated silica were the most effective viscosity agents.

2.4.3 Testing of Flowability of SCC

The key to success in manufacturing a self-compacting concrete lies mainly in its flow properties. The flow properties-workability and rheology need to be well examined. The workability of SCC is expressed in terms of the following attributes: slump flow diameter, flow time, segregation resistance, passing ability, and filling ability. The workability for SCC should be tested for at least two or three attributes with the help of various tests. Below is a brief summary of the more common tests currently used for assessment of workability of SCC (Ferraris *et al.*, 2000):

2.4.3.1 Slump Flow test

The basic equipment used is either same as that used for the conventional slump test (ASTM C 143) or a cone with proportionally smaller dimensions is used for the slump flow test of SCC. The procedure to carry out the test and the interpretation of results has been discussed in detail in Chapter 3. The slump flow test can give an indication as to the flowing ability of SCC and an experienced operator can also detect susceptibility of the mix to segregation. However, this information cannot be obtained from numerical results alone, a substantial previous experience in using the test and carrying out construction in SCC is essential.

The test does not appear to be sensitive enough to distinguish between SCC mixes and superplasticized fluid (but not self-compacting concretes) that can be prone to segregation, which all can reach values of flow between 550 mm to 750 mm. To reduce confusion in assessing and quantifying the slump flow test for SCC, researchers have developed a simple parameter known as Visual Stability Index (VSI) to define the stability of SCC mixture. The VSI is simply a visual rating from 0 to 3, in 0.5 increments, of the stability of the mixture (Daczko, 2002). Table 2.6 gives the breakdown of the different levels of VSI, with detailed descriptions for stable and unstable mixes. The VSI can be considered as a static stability index and should be noted by observing the concrete in a wheelbarrow or the mixer after some period of rest time (Khayat, *et al.*, 2004). However, the collective opinion amongst researchers is that though slump flow test does not offer sufficient information on segregation.

Table 2.6 Visual stability index and criteria (ASTM C1611)

Rating	Criteria
0	No evidence of segregation in slump flow patty or in mixer drum or wheelbarrow.
1	No mortar halo or aggregate pile in the slump flow patty but some slight bleed or air popping on the surface of the concrete in the mixer drum or wheelbarrow.
2	A slight mortar halo (< 10 mm) and/or aggregate pile in the slump flow patty and highly noticeable bleeding in the mixer drum and wheelbarrow.
3	Clearly segregating by evidence of a large mortar halo (>10 mm) and/or a large aggregate pile in the center of the concrete patty and a thick layer of paste on the surface of the resting concrete in the mixer drum or wheelbarrow.

2.4.3.2 L-Box test

This method uses a test apparatus comprising of a vertical section and a horizontal trough into which the concrete is allowed to flow (on the release of a trap-door) from the vertical section while passing through reinforcing bars placed at the intersection of the two sections of the apparatus. Numerous L-boxes of widely different dimensions have been tried. Bui *et al;* (2002) used this test in conjunction with a penetration apparatus to test the segregation resistance of SCC. SCC mixtures with variations in coarse to total aggregate ratio, paste volume, type and content of mineral admixture, aggregate combination as well as water cement ratio were studied for segregation resistance in the vertical and horizontal direction. It was observed, from the penetration test results, that zones of satisfactory and poor segregation resistance can be clearly divided. The method reduces testing time and laboratory work considerably. It is also helpful in distinguishing between SCC mixtures with different coarse-total aggregate ratios, different water-cement ratios and different materials.

2.4.3.3. V-funnel test:

The V-funnel (See Figure 2.7) is simple test where the concrete is allowed to flow from a funnel of standard dimensions under its own weight (Jin and Domone, 2002). The flow time is measured which is defined as the time between the flow starts and daylight being first visible when looking vertically down through the funnel. There can be operator errors in measuring the time by this method. This test is also used to ascertain the viscosity of the mix. Typically, SCC mixes are designed with flow times between 5 - 7 s are defined to be having acceptable viscosity. Most researchers use combinations of slump flow and funnel time to obtain optimum self compactability.

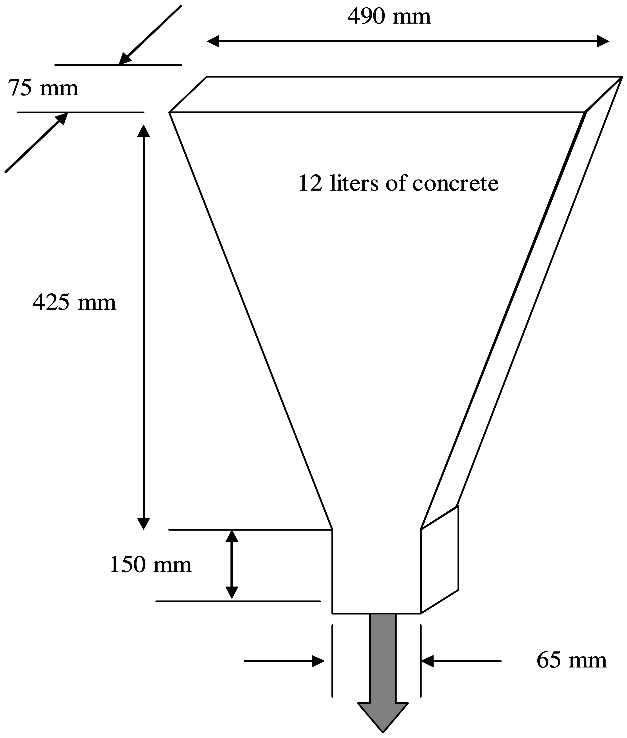


Figure 2.7 V-funnel test apparatus

2.4.4 Sensitivity of Self-Consolidating Concrete to Production Variables

The physical and chemical properties and the amounts of concrete ingredients affect the rheological behavior, stability, flowability and segregation resistance of SCC (Tattersall, 1991). Typically SCC is designed in such a way that all the required properties are met with optimal usage of constituent materials. Therefore, at full scale production it is of primary interest to have a good understanding of the effects of variability of the quality of concrete constituents on the resulting properties of concrete. Based on the reported data, the material-related parameters that exhibit the largest variations in normal concrete manufacturing are as follows (Emborg, 2000):

a. aggregate grading curve,
b. aggregate moisture content,
c. total water content, and
d. cement properties

The common experience of researchers in regards to robustness of self-consolidating concrete (SCC) has been that when mixing, the overall margins in production are smaller. It has been observed (Emborg, 2000; Nishizaki *et al.*, 1999) that SCC is more sensitive to any deviation from target recipe and from mixing techniques than ordinary concrete. Also, a more complete documentation for component materials, final product and quality control of the fresh concrete properties needs to be maintained. Due to high cementitious content, SCC typically requires high mixing time as compared to normal concrete which can lead to a reduction in the capacity of the concrete plant and can cause supply bottlenecks at the site (Lowke and Schiessl, 2005). The robustness of self compacting concrete is dependent on various factors such as (Deshpande and Olek, 2005; Emborg, 2000):

a. mixing equipment,
b. mixing time and mixing sequence of addition of different types of admixtures,
c. total water content in the mixture,
d. variations (within the specified limits) of aggregate grading curve, and
e. aggregate moisture content.

In the following section published literature on the effect of mixing equipment and mixing time on variations observed in the fresh and hardened concrete properties will be examined. Also in this section, the influence of variation of moisture content and aggregate grading curve will be discussed in detail through published literature.

2.4.4.1 Mixing Equipment

In general, two types of mixers are used all over the world for production of concrete. Mixing equipment could be of a free-fall type (tilting drum) mixer or a forced paddle mixer (Emborg, 2000; Takada *et al.*, 1998). The free-fall type of mixers, sometimes called as “gravity mixers”, are predominantly used larger plants in northern Europe and southern Asia at larger plants (Emborg, 2000; Takada, *et al.*, 1998). Paddle mixers are of two types-forced pan mixer and pugmill mixers. The forced pan mixers are of the planetary form, with agitators, whereas the pugmill mixers are through mixers, with one or two rotating shafts.

Takada *et al*; (1998) have performed a laboratory investigation of the effect of mixer type on the fresh concrete properties. The study was conducted using a pugmill type mixer with horizontal dual axes and a tilting drum mixer. Some of the conclusions made in this study are as below:

a. It was observed that the gravity type mixer resulted in SCC with very high V-funnel flow times as compared to SCC mixed in pug mill mixer with the same composition and mixing sequence.
b. Even though the V-funnel flow times of SCC obtained by using pug mill mixer were low, it was observed that for some of the mixture compositions the mixture exhibited segregation tendencies.
c. To achieve the same slump flow (65 ± 3 cm), less amount of superplasticizer (SP) was needed in the gravity mixer.

d. Tilting drum mixer could be used to produce SCC of acceptable properties with higher water to powder volume ratio and a lower SP dosage as compared to the pugmill mixer.

Takada *et al* (1998) have related the requirement of low dosage of SP for tilting drum mixer and the high viscousness of the resulting mixtures to its low mixing efficiency and its effects on the dispersion of the powder particles. The mixing action in the tilting drum mixer is not as vigorous as the mixing action in forced pan mixers, and can result in agglomeration of powder particles in the paste phase. For the same overall mixture composition, this produces SCC that is more viscous than SCC obtained from pan mixers. The agglomerates have less adsorptive surface area for the polymer chains of SP to attach themselves to and as a result, a smaller amount of SP is sufficient to obtain the same slump flow. Also, in case of intensive mixing that takes place in pan mixers, polymers of the SP that get attached to the initial hydration products of cement particles are torn away from the surface due to the vigorous rapid mixing creating smaller particles of the paste phase. The increase in the number of smaller particles increases the surface area of the paste phase, leading to a higher demand of SP. This results in higher SP dosage requirement for pan mixers.

Emborg, (2000), while reviewing the same study (Takada, *et al.*, 1998), commented on the fact that the dosage of SP is influenced by the mixer type is well-documented, but observed that a lower dosage is required for gravity mixer is new and further research needs to be carried out. He further cautions the reader that the influences of type of mixer on full scale production are not the same as what are seen in cases when laboratory mixers are used. According to Emborg (2000), plant mixers provide for an increased mixing efficiency compared to laboratory conditions even though a paddle mixer or another type of forced mixer has been used. In Europe, (Emborg, 2000) comparisons of w/c = 0.45 SCC were made at a plant using a twin-shaft mixer (3 m^3) and a free fall mixer (6 m^3). Almost no differences in terms of stability or workability were obtained for the batches mixed for the same length of time.

2.4.4.2 Mixing Sequence and Mixing Time

Some limited information can be found in the literature on the issue of mixing sequence and length of mixing time on the properties of SCC. Although full scale and laboratory mixes have been reported in the literature (Billerberg *et al.*, 1999; Domone and Jin, 1999; Emborg, 2000; Takada, *et al.*, 1999). This section only presents the results from laboratory tests.

The effect of mixing sequence and a mixing time on the properties of SCC were studied by Takada *et al* (1998) using a gravity mixer (G) and a forced paddle mixer (F). The overall combination of variables used in their study is shown in Figure 2.8. Values in brackets indicate shorter mixing times for the same sequence of mixing. It was observed that for mixes with the same ratio of the volume of water to volume of powder (V_w/V_p) mixes prepared in gravity mixers required longer mixing times (G7.5, G3.5) and lower SP dosages but achieved higher slump flow values and longer V-funnel flow times as compared to shorter mixing times (G5.5, G2.5).

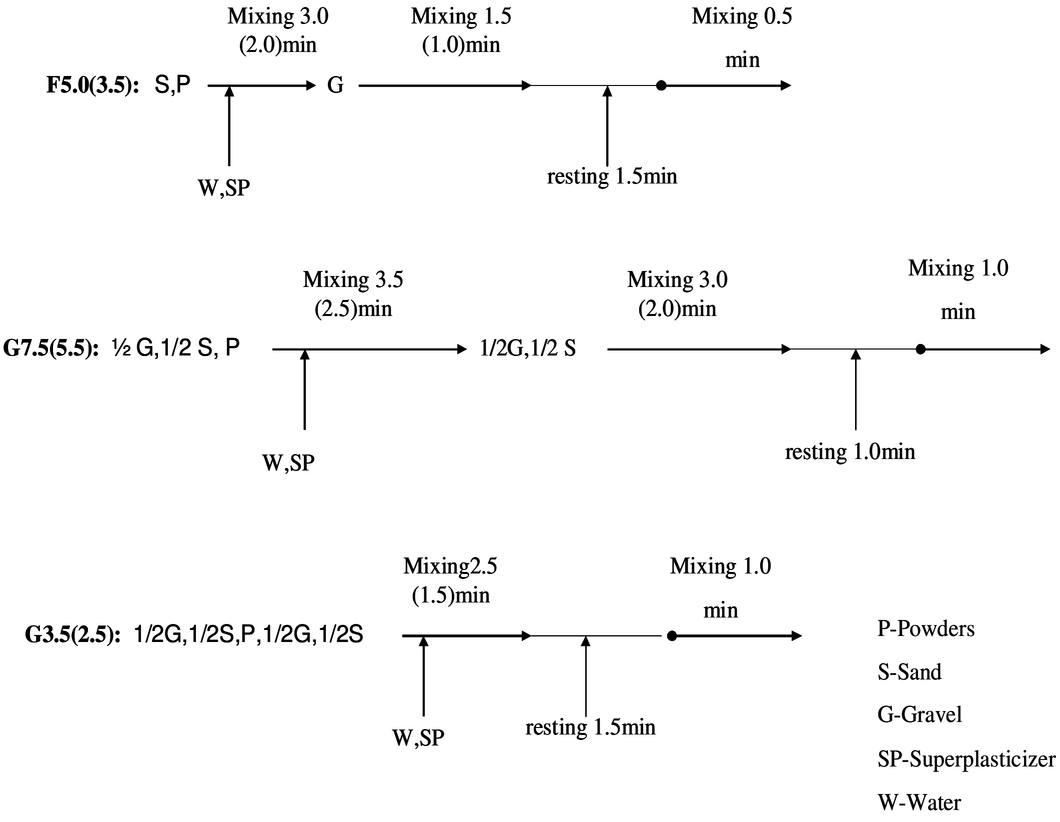


Figure 2.8 Mixing sequences adopted by Takada *et al;* (1998)

In case of forced pan mixers, it was observed that in order to obtain the same level of deformability of the SCC, longer mixing times (F5.0) required higher dosages of SP than shorter mixing times (F3.5) for the same (V_w/V_p). In the results published by Takada, *et al.*, 1998, the authors concluded that though the presented tendency of the forced pan mixers was clear, the magnitude of influence was not very large.

The effect of delay in the time of addition of SP on the slump flow and V-funnel time was studied by Domone and Jin (1999). In their study, the delay in the time of addition of SP varied from zero minutes to six minutes in steps of one minute. Figure 2.9 shows the mixing sequence for the case of SP addition 2 minutes after the adding all powders, sand and 80% of water. Eighty percent of the mix water was added at the start of mixing, and the remaining 20% was added with the SP.

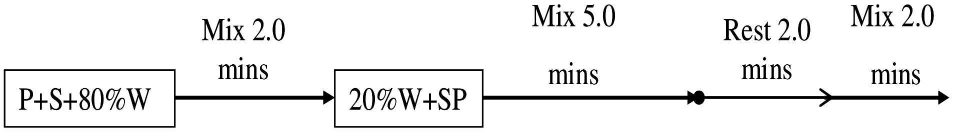


Figure 2.9 Mixing sequence adopted by Domone and Jin (1999)

The study used three different types of SP: naphthalene-based SP, melamine-based SP and polycarboxylic ether-based SP. It was observed that delayed addition of SP increased their effectiveness as measured by both the spread and V-funnel results. The optimum addition time 'window' was found to be 2 to 4 minutes for the naphthalene- and melamine-based admixtures, whereas for polycarboxylic admixtures the window was between 0 and 0.5 minutes.

Chopin and his co-workers (2004) used 36 different SCC mixtures to address the issue of the required length of mixing time to achieve a homogenous mixture. The parameters varied in the study included: the quantity of powder, use of limestone filler or silica fume (including various forms of silica fume) and the type of SP and dosage. To analyze the effects of these parameters a stabilization time (t_s) of power consumption (P) of the mixer was defined by the authors as the time at which the power-time curve reaches the asymptote as shown in Figure 2.10. The value of ε , i.e., the time differential of the ratio of the power consumed at time t to the power consumed at t = ∞, is fixed by the authors (Chopin, De Larrard, and Cazacliu, 2004) to achieve a minimum value of t_s = 35 s.

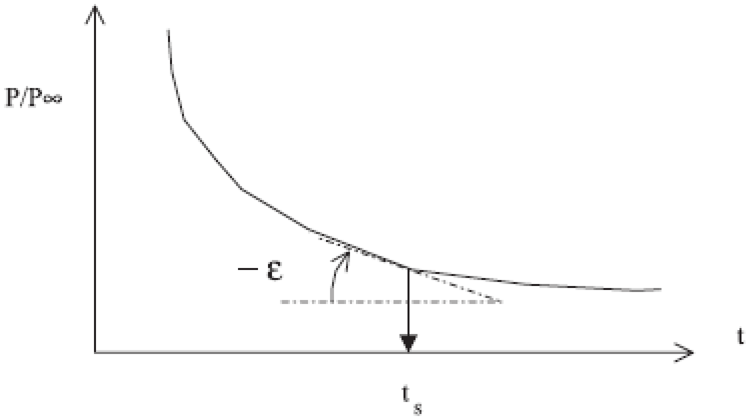


Figure 2.10 Definition of stabilization time (Chopin *et al.*, 2004)

The authors have concluded that although the SCC mixtures will generally require longer mixing times than the conventional concrete mixing, their mixing time can be reduced by:

- increasing the fine particle content, with a constant w/c,
- increasing the total water amount, and
- replacing part of the cement by silica fume.

In their recent publication, Lowke and Schiessl (2005) presented a novel approach of hybrid mixing sequences to reduce the mixing time required for SCC mixtures. In hybrid mixing sequences, mixing is carried out in several partial processes with varying mixing intensity. It was observed by the authors that increasing the velocity of the rotating paddles of the mixer helps in accelerating the dispersion of water and superplasticizer. Once the dispersion has been completed, the velocity of the paddles can be reduced to homogenize the mix. Thus, in hybrid mixing sequences the velocity of the paddles is increased after the addition of superplasticizer for a total of 20 s of the mixing process and for the next 30 s the mixing paddle velocity is reduced.

2.4.4.3 Influence of the Aggregate Grading Curve

Ekman (as cited in Emborg, 2000) studied the effect of variation of aggregate grading and its moisture content on flow and segregation resistance of SCC. He monitored the variations in the grading curve and aggregate moisture content at selected concrete plants (Figure 2.11 and Figure 2.12) and simulated these variations in the laboratory mixtures.

The results of these studies for the slump flow, T_{50} and L-box test values are presented in Figures 2.13a - 2.13c. The results from the slump flow test indicate a strong decrease in the measurement value for -1% of moisture content. The graph also indicated that the middle-range aggregate curve is more sensitive to moisture content variation.

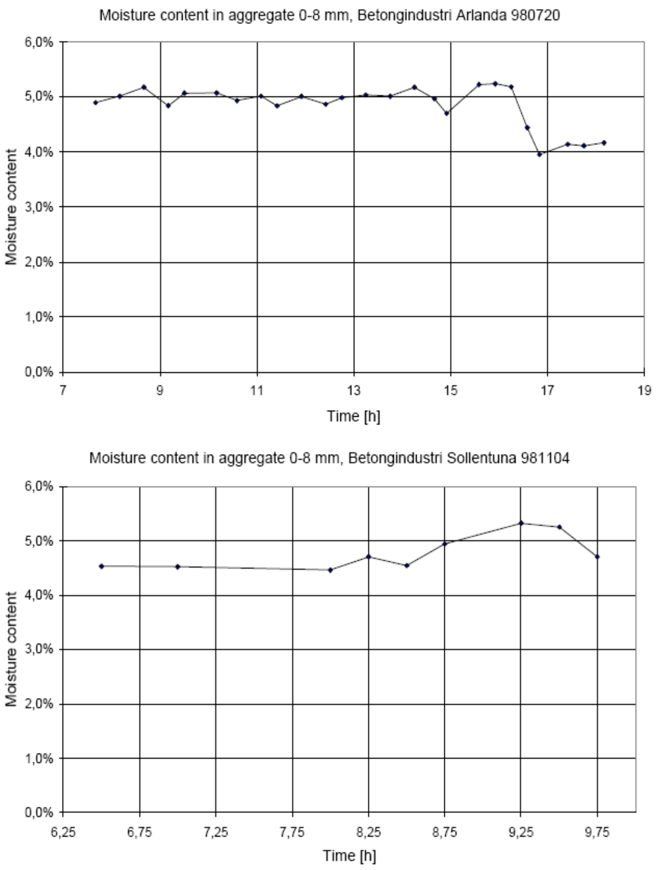


Figure 2.11 Variation in the aggregate moisture contents at two concrete plants in the Stockholm area (Emborg, 2000)

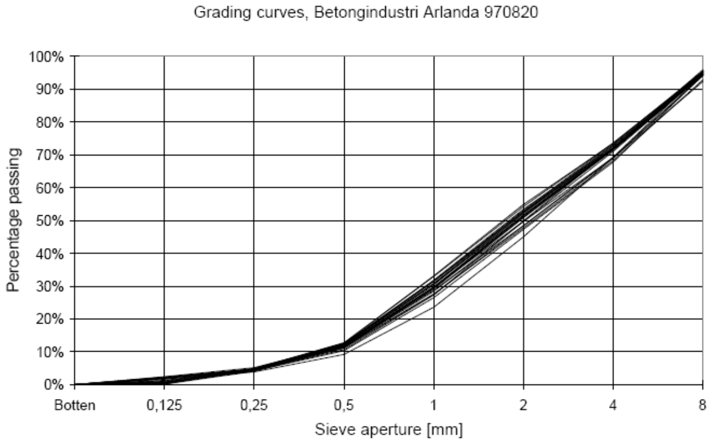
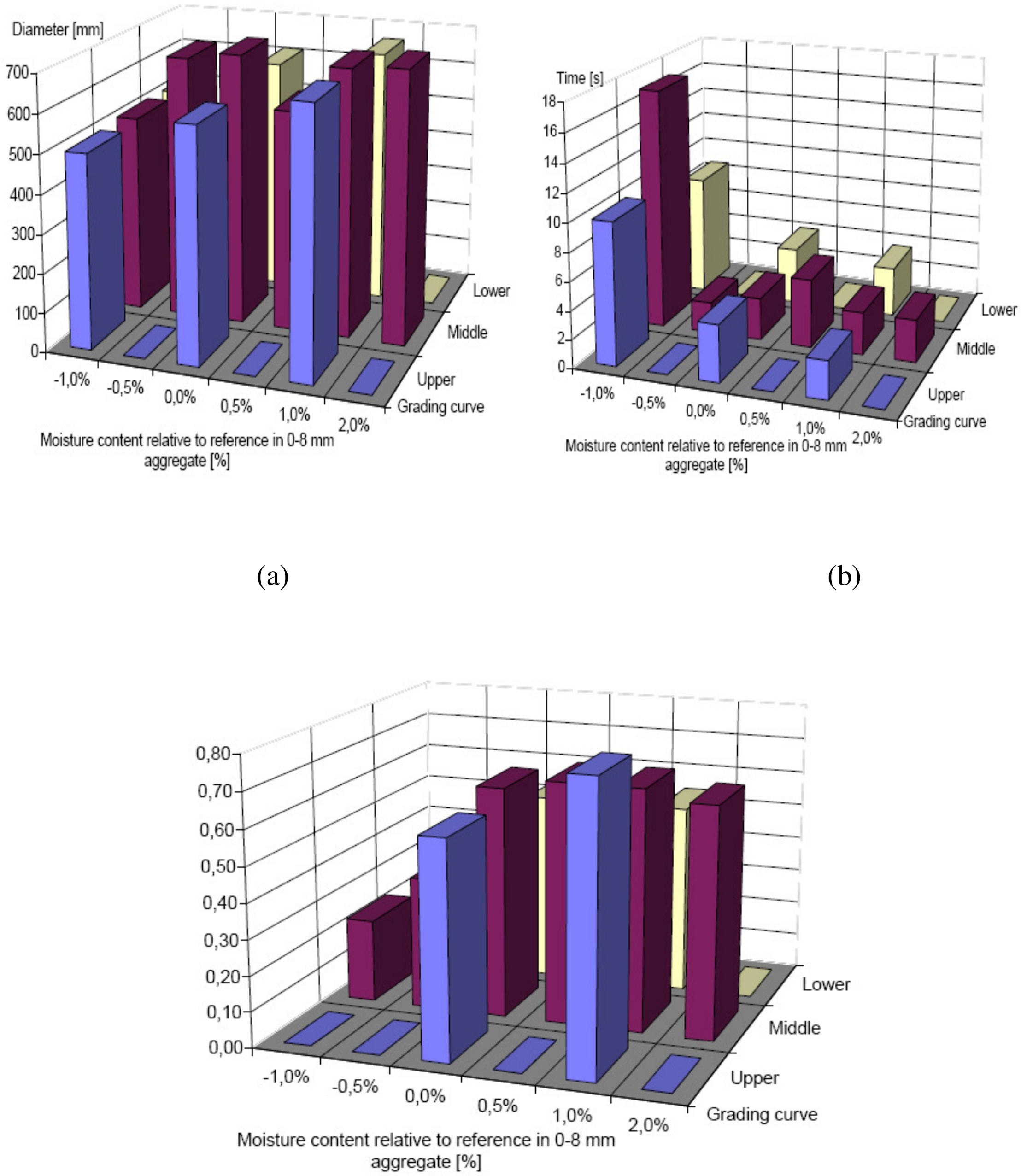


Figure 2.12 Variation in grading curve at one concrete plant (Emborg, 2000)



(a)

(b)

(c)

Figure 2.13 Results from (a) slump flow, (b) T_{50} tests and (c) L-box test results (zero value indicated no testing), (Emborg, 2000)

Influence of changes in moisture content on T_{50} is strong, especially when the moisture content is reduced from -0.5% to -1.0% with T_{50} of 16 seconds for -1% as compared to about 4 seconds for -0.5%. Blocking is also influenced by decrease in moisture content and is very low for -1%, whereas for moisture content amid 0% to 2.0% the L-box tests do not show a large variation in the data. It can be inferred from this study that the maximum allowable variation in moisture content is 0.5%.

Mori and co-workers (1996) measured the slump flow at 0, 60 and 120 minutes after mixing for mixtures with variable fineness modulus (FM) of fine aggregates. The authors observed that for mixtures with w/c= 0.35 containing a high range water reducer and aggregates with low FM, the slump flow values were low as compared to those with similar mixtures but having a VMA.

2.4.4.4 Aggregate Moisture Content and Water Content

Aggregate moisture content affects the total water content in two ways:

- Moisture content of the aggregate is higher, thereby reducing the total water content, and
- Moisture content of the aggregate is low, thus leading to higher free water content.

Mori *et al;* (1996) examined mixes with 74 different types of aggregate and varying water absorption values. The authors concluded that the slump flow value tends to decrease with an increase in water absorption of fine aggregate for mixtures with 0.35 water-cement ratio as opposed to 0.5 water-cement ratio. A strong influence on slump flow was observed by Sakai *et al.* (1994), when the amount of water was changed by ± 5 kg/m^2. These variations were reduced when a viscosity agent was added to these mixtures. It was concluded by the authors that if changes in water content go unnoticed, the water-cement ratio is changed, which affects the strength of hardened concrete. Similar observations of slump flow were made by Ushijima and co-workers (1995) when they varied the amount of water added to the mixture in such a way that it resulted in change of aggregate moisture content between -1% to +1.5%. The slump flow increased nearly 100 mm when the surface moisture content was increased by 1%.

Highuchi (1998) studied the effects of surface moisture of aggregates on concrete properties and the electric power consumed by the mixer. It was observed that the low viscosity of the mix was associated with high values of electric power consumption. The values of power consumption of the mixer was used by Nishizaki *et al.* (1999) to adjust the composition of SCC, which varied due to fluctuations in the moisture content of the fine aggregate. Power consumption data of every batch was collected and the SCC properties were controlled by adjusting the water content as a function of the power consumption values.

2.5 Gaps in Existing Knowledge Regarding Repair Materials

Concrete pavements develop loss in load transfer leading to faulting and cracking over a period of time. Loss in load transfer and faulting can be reduced by adopting dowel bar retrofit DBR repair techniques. Many states have adopted comparable designs for DBR systems. In general, most of these systems consist of placing three dowel bars at the mid-depth of the slab in each of the wheel-path. Several different types of repair materials have been approved and used in DBR applications by individual the state DOTs. Limited studies have been carried out to evaluate the long term performance of the repair materials used in the DBR systems.

Many factors are responsible for the successful performance of the DBR repairs. Some of the main factors that include the dowel configuration, diameter of dowel bar, type of repair material used, quality of installation, etc. In most cases, a change in dowel configurations does not affect the load transfer efficiency to a large extent. After carrying out extensive research few state DOTs have adopted a configuration of three dowel bars in both wheel paths.

Literature reviewed in section 2.3 reflects the fact that failure of DBR systems occurs largely due to poor bond between the old and new concrete. The loss of bond can be attributed to various factors such as inadequate vibration, early age failure of the repair material due to low rate of strength gain, aggregate content, development of shrinkage stresses and other durability issues such as, freeze-thaw cycling, etc. To achieve good performance of the DBR, it is crucial to study the bond properties between the old and the new concrete from micro as well as macroscopic perspectives.

The parameters that need to be considered while selecting the repair material for DBR systems are the setting time, slump flow, strength gain at prevalent ambient temperatures, ease of mixing, need for vibration, and curing requirements. Since, the highways have to be opened to traffic without long downtime, it is essential that a rapid setting material be adopted for repair purposes. Though initial high strength is required, volumetric stability (low shrinkage) is also important. The freeze thaw durability of the repair material is considerably reduced if it is extended by addition of aggregates. The published information on the approximate values of extension that can be adopted to ensure a freeze-thaw durable is limited.

Based on the literature review presented in this chapter, it may be concluded that it is essential to carry out research on development of repair materials that will gain strength rapid, will be flowable and have low shrinkage values. From this perspective, the use of self compacting concrete as a repair material seems to be a viable option. Literature survey carried out for this study suggests that SCC has not been largely studied for use as a repair material except for a few published cases (Khayat, and Morin, 2002; O'Flaherty and Mangat, 1999; Walraven, 2002) as previously discussed in section 2.4.1.

In recent years, Degussa Co. has started marketing a product named "4X4® concrete". The concrete is made from locally available materials and the chemical admixtures are provided by the company. It is claimed by the manufacturer that the product achieves 400 psi flexural strength at the end of four hours with the help of the accelerators added during mixing. However, this product uses large size aggregate (12.5 mm) which can be a constraint when the product has to be adopted for repairs of shallow depth slots for use in congested areas. Review of the literature indicated that there are no published studies on the development of SCC with addition of accelerators for rapid strength gain.

CHAPTER 3: EXPERIMENTAL PROCEDURE

3.1 Introduction

This chapter explains in detail the research plan adopted for the study, materials used, the methodology adopted for development of mixture proportions and the test methods employed to evaluate various properties of different rapid-setting repair materials. Figure 3.1 gives an overview of the research plan adopted to fulfill the objective outlined in Chapter 1. As mentioned in Chapter 1, the research plan was divided in to two phases: Phase I - Study of commercial rapid-setting materials and Phase II- Development of rapid-setting self-consolidating concrete (RSSCC). Each phase was, in turn, sub-divided into two steps.

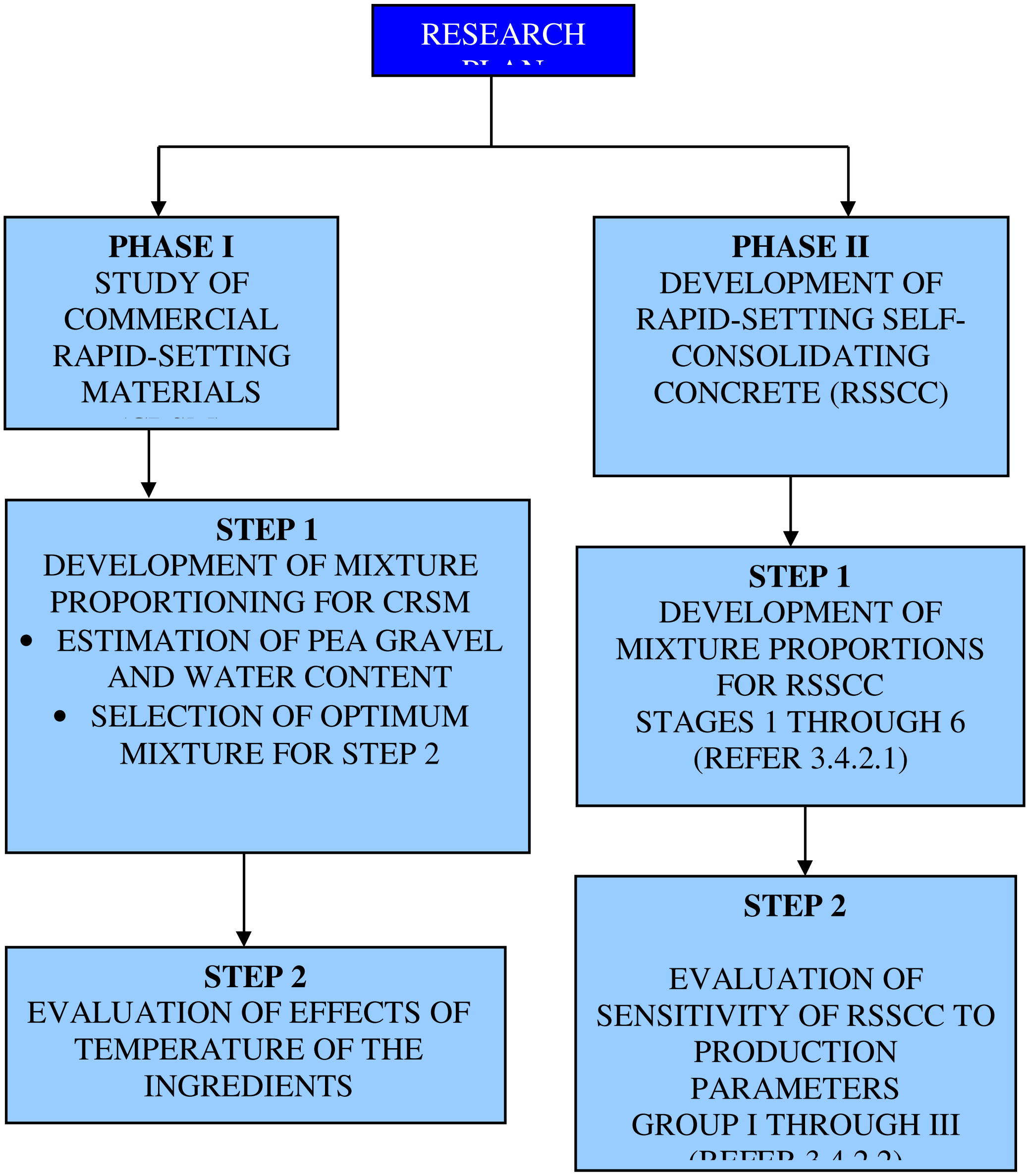


Figure 3.1 Block diagram of the research plan

Phase I consisted of developing mixture proportions and assessment of fresh and hardened properties of concretes made using commercially available rapid-setting materials (CRSMs). To better stimulate temperature conditions that may be present at the job site during placement of repair patches, these materials were pre-conditioned at three different temperatures 10°C, 23°C and 40°C. Since the repair materials used typically develop a substantial amount of heat during initial stages of setting and hydration, it was important to evaluate to what extend their behavior will be influenced by their initial temperature. Phase I experiments were carried out in two steps: Step 1 and Step 2. Step 1 consisted of development of mixture proportions for CRSMs by varying the amount of the pea gravel and water content. Step 2 involved study of the effects of temperature of the ingredients using selected mixtures intensified in Step 1.

Phase II also consisted of two steps. Step 1 of Phase II involved development of rapid setting self compacting concrete (RSSCC). The focus of Step 2 of Phase II was on evaluation of sensitivity of RSSCC to variation in production parameters such as aggregate moisture content, aggregate gradation and remixing after a period of rest time.

The testing regime for both Phases included assessment of various fresh and hardened concrete properties such as slump or slump flow, setting time, rate of compressive strength development at various ages, drying shrinkage, cracking potential, freeze-thaw resistance and slant shear bond strength.

3.2 Materials

In this section, the materials used in the research program are described. Properties of the ingredients used in preparation of mixtures in Phase I and Phase II are specified in sections 3.2.1 and 3.2.2, respectively. Section 3.2.1 also includes detailed description of the process of selection of CRSMs used in this study.

3.2.1 SELECTION AND PROPERTIES OF COMMERCIAL RAPID SETTING MATERIALS (PHASE I)

For the Phase-I part of the project four proprietary rapid setting materials were selected for an extensive analysis of their properties such as slump, setting time, rate of development of compressive strength, cracking potential, slant shear bond strength and durability to freezing and thawing. These materials were chosen after carrying out an in-depth analysis of the specifications and approved patching materials from nine state DOTs (Indiana, New York, Washington, California, South Dakota, Ohio, Nebraska, Michigan, Kansas). Published reports from various state DOTs on performance of dowel bar retrofit technique were also examined to determine the field performance of different rapid-setting materials (Eacker, 1999; Embacher, E., 2001; Embacher, R. A. *et al.*, 1999; Glauz *et al.*, 2001, 2002; Wilson & Toepel, 2002). Another factor that was taken into account during the selection process was a desire to incorporate rapid-setting materials of different composition and from different manufacturers. After consideration of all of the above factors, the following materials were chosen:

1. SET®45 (MAGNESIUM PHOSPHATE CEMENTS TYPE MATERIAL, REGULAR(SET®45 R) AND HOT WEATHER (SET®45 HW) TYPE)
2. THOROC™ 10-60 (ALUMINA CEMENT/PORTLAND CEMENT BASED MATERIAL)
3. FIVE STAR® HIGHWAY PATCH CEMENT (FSHPC) (HYDRAULIC CEMENT BASED MATERIAL), AND

4. AHT-HIGHWAY DOWEL BAR RETROFIT MORTAR™ (HDBR) (CALCIUM ALUMINATE / PORTLAND CEMENT BASED MATERIAL)

SET® 45 is the only material amongst the chosen rapid setting materials which is supplied in two different formulations. The selection of a particular formulation depends on the temperature conditions at site. For applications where ambient temperature conditions are below 29°C a regular formulation (SET® 45 R) is used. For applications where ambient temperature conditions are in the range from 29 to 38°C a hot weather formulation (SET®45 HW) should be used. In this research, SET ®45 HW was used only in those mixtures which were prepared using materials pre-conditioned at 40°C.

Only one of the CRSMs used (Five Star Highway Patch®) was supplied without any aggregate added. All other selected materials were supplied premixed with aggregates i.e. rapid-setting cement mixed with aggregate. The pre-mixed aggregate used is typically silica in crystalline quartz form. Figure 3.2 shows the grain size distribution of the materials which were in the premixed form. All the CRSMs which were tested had nearly similar gradation. ThoRoc™10-60 had a relatively uniform gradation in comparison to SET®45 and HDBR.

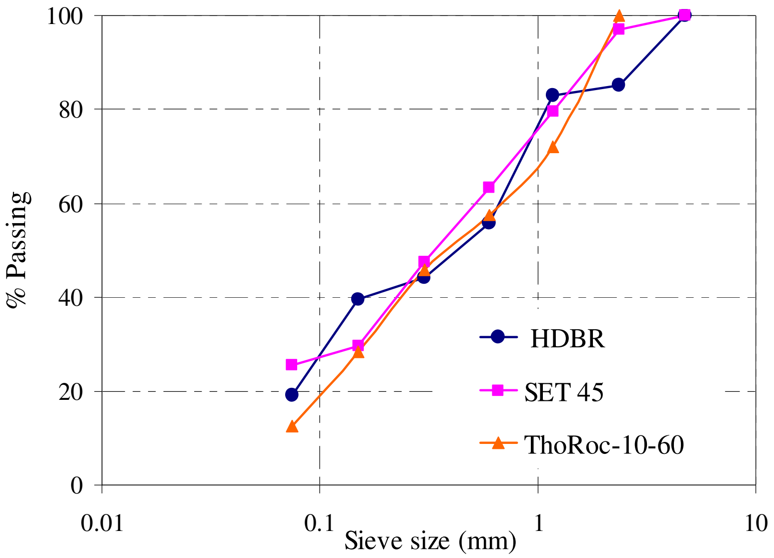


Figure 3.2 Gradation of rapid-setting cements

For repair depths more than 50 mm (2 in.), the manufacturers suggest extension of the repair concrete by adding pea gravel. Allowable amounts of clean, washed and well-graded pea gravel are provided by the different manufacturers (refer to Appendix D). This research was confined to study of rapid-setting concrete for repair depths more than 50 mm (2 in.) only. Hence, testing and evaluation of repair mortar i.e. without any pea gravel addition was not performed.

The properties of natural sand and pea gravel used in Phase-I are shown in Table 3.1 and their grain size distributions are shown in Figure 3.3. The pea gravel used for this study had minimum size (D_{max}) of 9.5 mm and about 65% of its mass was was retained on sieve size 4.75 mm. The natural sand was well graded and its gradation curve was within the Indiana Department of Transportation gradation limits for #23 sand. This sand was used for mixtures with Five Star Highway Patch Cement ® (FSHPC) since as is indicated earlier; this material was supplied without any aggregate extension.

Table 3.1 Properties of aggregates

PROPERTY	NATURAL SAND	PEA GRAVEL
SSD ABSORPTION (%)	1.85	2.43
SSD SPECIFIC GRAVITY	2.70	2.70

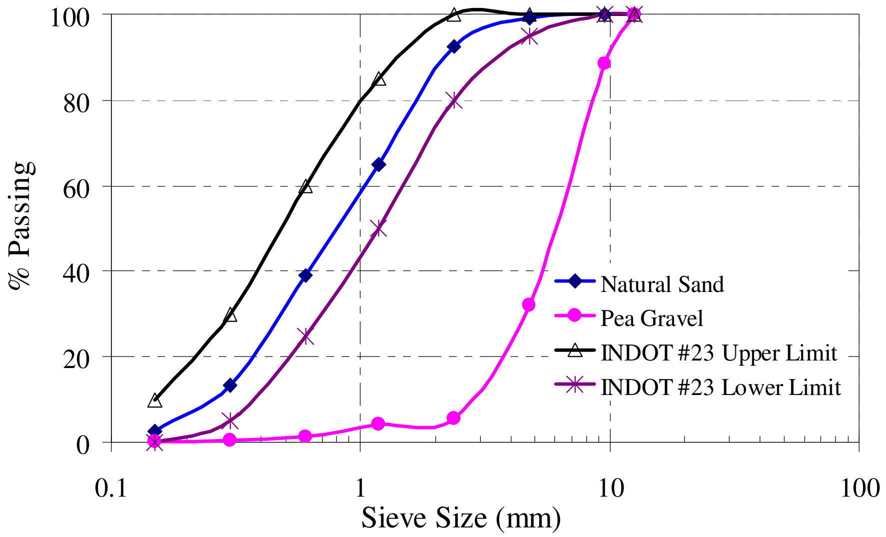


Figure 3.3 Gradation of sand and pea gravel

Table 3.2 gives the manufacturers recommended ranges for water content and pea gravel extension for all patching materials except FSHPC. The maximum water content for SET® 45 R as well as SET® 45 HW is fixed by the manufacturer at 1.9 L per one bag (22.7 kg) of the material and it should not be altered. Similarly, the manufacturers of ThoRoc™ 10-60 and HDBR products also fixed the water content at 2.6 kg per 22.7 kg of repair material, but they do allow addition of water up to 0.47 L and 0.2 L per 22.5 kg of material, respectively. The mixture proportions adopted for Five Star® Highway Patch are given in section 3.4.1.

Table 3.2 Water and aggregate content for patching materials

PATCHING MATERIAL	**ALLOWABLE WATER (L)**	**ALLOWABLE AS PER MANUFACTURER PEA GRAVEL EXTENSION (% OF MASS OF 1 BAG)**
SET® 45	1.9	60
HDBR	2.6*	60-100
THOROC™ 10-60	2.6**	50-100

**- ADDITIONAL WATER ALLOWED (UP TO 0.20 L)*
***- ADDITIONAL WATER ALLOWED (UP TO 0.47 L)*

For SET®45 R and HW the allowable extension is fixed at 60% by mass of 1 bag and for ThoRoc™ 10-60 the allowable pea gravel extension as per the manufacturer is 50 to 100% by mass of 1 bag of mortar. For HDBR, the range of 60 to 100 was ascertained after discussions with the manufacturer.

3.2.2 PROPERTIES OF MATERIALS USED TO PRODUCE RSSCC (PHASE II)

For the RSSCC mixtures two, types of cement: Type I and Type-III, confirming to ASTM C 150 were used. The physical and chemical properties of the cement are given in Table 3.3.

Table 3.3 Physical and chemical properties of portland cement.

TEST	**TYPE I**	**TYPE III**
FINENESS (CM^2/G)	3600	6210
AUTOCLAVE EXPANSION		-0.010
COMPRESSIVE STRENGTH, MPA		
1-DAY	16	29
3-DAY	26	39
7-DAY	32	47
SETTING TIME		
INITIAL, MIN	103	84
FINAL, MIN	204	158
TRICALCIUM SILICATE (C_3S)%	58	59
DICALCIUM SILICATE (C_2S)%	12	14
TRICALCUIM ALUMINATE (C_3A)%	8	10
TRICALCIUM ALUMINOFERNITE (C_4AF)%		7

The other cementitious materials used in this project were densified silica fume (SF) manufactured by Elkem Materials and micro-fine fly ash (MFA) manufactured by Boral Materials Technologies which is marketed as Boral Micron^3™. Silica fume used had a specific gravity of 2.2 and MFA had a specific gravity of 2.57. The mean particle size of SF was 0.15 μm and for MFA it was 3 μm. Table 3.4 gives the chemical analysis of silica fume and micro-fine fly ash used in this study.

Table 3.4 Chemical analysis of silica fume and micro-fine fly ash

	SILICA FUME	**MICRO-FINE FLY ASH**
CHEMICAL ANALYSIS BY MASS (%)		
SILICON DIOXIDE (SIO_2)	93.07	54.08
ALUMINUM OXIDE (AL_2O_3)	0.62	25.33
FERRIC OXIDE (FE_2O_3)	0.41	4.92
CALCIUM OXIDE (CAO)	0.66	8.58
MAGNESIUM OXIDE (MGO)	1.16	1.79
SODIUM OXIDE (NA_2O)	0.16	0.50
POTASSIUM OXIDE (K_2O)	0.79	1.07
SULFUR TRIOXIDE (SO_3)	<0.01	0.93
TITANIUM DIOXIDE (TIO_2)	<0.01	
PHOSPHOROUS PENTOXIDE (P_2O_5)	0.10	
STRONTIUM OXIDE (SRO)	<0.01	
CHROMIC OXIDE (CR_2O_3)	0.02	
ZINC OXIDE (ZNO)	0.10	
ALKALIES AS NA_2O	0.67	1.20
LOSS ON IGNITION (950°C)	2.71	0.66

As mentioned in Section 2.4, BASF Admixtures (formerly Degussa Co.) manufactures a rapid setting concrete called 4x4™ Concrete System. For this project, an attempt was made to develop RSSCC based on this product. After consultations with the corporation, the chemical admixtures adopted for preparation of 4x4™ Concrete System were also used for Phase-II and included:

1. High range water reducers (HRWR) – Two types of polycarboxylate based HRWR were adopted in this study Glenium® 3200 HES and Glenium® 3400. The HRWR Glenium® 3200 HES was used for Stage I mixtures only (refer to Section 3.4.2.1). Glenium® 3400 is recommended in the final mixture proportions for RSSCC.
2. Viscosity Modifying Agent –RheoMac® VMA 362
3. Air entrainer (AE) – Micro Air® conforming to ASTM C 260
4. Non-chloride acclerator- Pozzolith® NC 534 containing calcium nitrate and conforming to ASTM C 494 Type C.
5. Shrinkage Reducing Admixture –Tetraguard® AS20

Three different sources of fine aggregate (Sand-1, Sand-2 and Sand-3) as well as two different sources of pea gravel with four different gradations (PG-1, PG-2, PG-3 and PG-4) were used to prepare the RSSCC mixtures. The selection of a particular aggregate source was a function of mixture design variables, as described in section 3.4.2 of this chapter. The specific gravities of Sand-1, Sand-2 and Sand-3 were 2.63, 2.70 and 2.65, respectively. The gradation curves of these sands are shown in Figure 3.4. Sand-1 was the coarsest of the three sands with the fineness modulus (FM) of 4.14. Sand-3 was the finest with FM of 3.70. The FM of Sand-2 was 3.87. The water absorption values of the sands were 1.8, 1.85 and 1.5% for Sand-1, Sand-2 and Sand-3, respectively. The gradation curves of all the three sands fit between the upper and lower gradation limits given in the Indiana Department of Transportation (INDOT) Standard Specifications for # 23 sand [11].

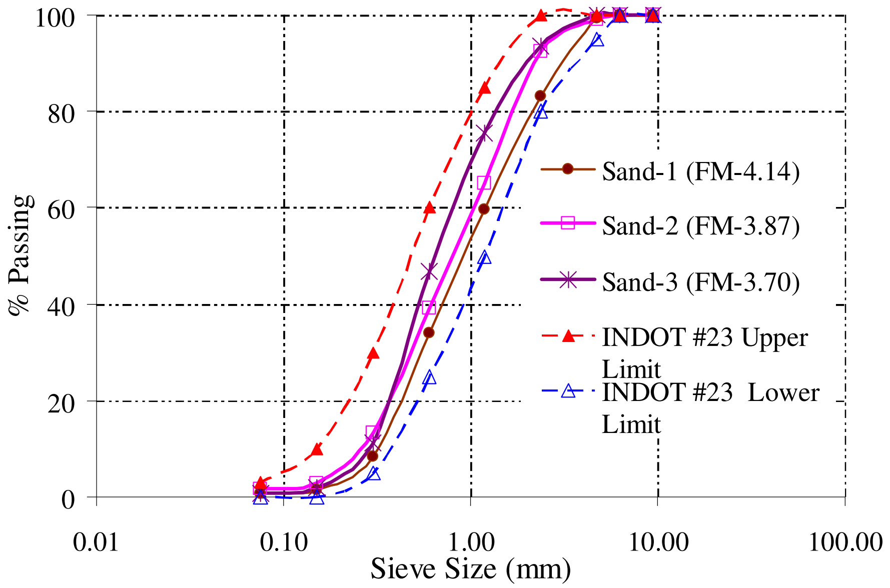


Figure 3.4 Gradations of various sands used in Phase II

The maximum diameter (D_{max}) of all pea gravel aggregates used was 9.5 mm. The specific gravities of PG-1, PG-3, PG-4 aggregates were all 2.70 as PG-3 and PG-4 were derived from PG-1 source by changing the gradation to obtain either coarser blend (PG-4) or a finer blend (PG-3) as shown in Figure 3.5. The gradation of PG-3 and PG-4 lies on the lower and upper limits of gradation for ASTM #8 aggregate as per ASTM C 38. The specific gravity of PG-2 aggregate was 2.68. The FM of the coarse aggregates was 5.45, 5.50, 5.67 and 6.05, respectively for PG-1, PG-2, PG-3 and PG-4 gradations. The water absorption of the pea gravels was 2.43 and 1.91% for PG-1 and PG-2 respectively whereas for PG-3 and PG-4 it was 2.51 and 2.64% respectively. The selection of a particular type of pea gravel was a function of the mixture design variables as described in section 3.4.2 of this chapter.

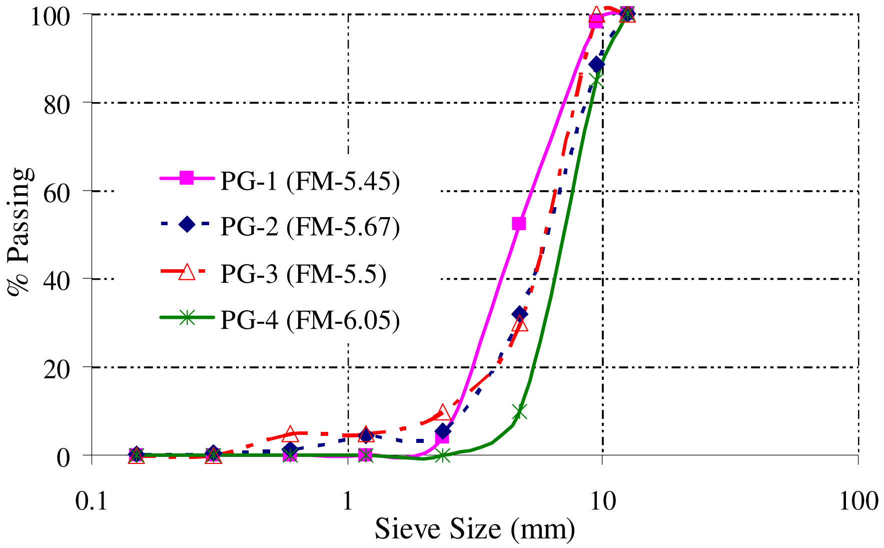


Figure 3.5 Gradation of pea gravels adopted in Phase II

3.3 Mixing Equipment

Typically, concrete volumes required for repair purposes are small and are therefore mixed on site. Figure 3.6a shows a mortar mixer (28 L capacity) used in this study. Mortar mixers of similar capacity are usually used in field applications that require preparation of small volumes of repair materials. The mortar mixer is a batch type of drum mixer with a horizontal axis of rotation (Ferraris, 2001). The drum of the mortar mixer is of tilting type with fixed blades. In the mortar mixer used in this study the drum is tilted for discharge of materials only and remains in a horizontal position during the mixing process.

Figure 3.6a Mortar mixer

Figure 3.6b Pan mixer

The pan mixer shown in Figure 3.6b is a typical laboratory pan mixer with 56 L capacity. The pan mixer has a counter current motion with the scraper fixed and the blades and the pan rotate. The type of mixer used for preparing different mixtures was a function of the variables discussed in section 3.4.

In an attempt to get an insight into the effects of aggregate moisture content and gradation on mixing efficiency of a given mixer, variations in electrical current levels during the mixing process were monitored using two different ampprobes. The AC current clamp ampprobe manufactured by Fluke® was used for monitoring the current for mixtures with w/cm of 0.31. The Ohio Systems® probe was used for monitoring the current for mixtures with w/cm of 0.36. The primary difference between these ampprobes was their sensitivity. For the Fluke® probe the sensitivity factor was 100 mV = 20 A and for the Ohio Systems® probe the sensitivity was 2.5 mV = 20 A. The measured variation in the current drawn by the mixer was converted to the power consumed by the mixer using the relationship below:

$$\text{Power} = \text{Voltage} \times \text{Amperage} \times 0.85 \times 0.86$$

WHERE: 0.85 = POWER FACTOR,
0.86 = EFFICIENCY FACTOR

3.4 Experimental Methodology

The experimental methodology adopted for the two phases of the study can be generalized as consisting of development of mixture design and the detail testing of properties of the mixtures. The following paragraphs give a detail account of the experimental methodology adopted for each phase.

3.4.1 Experimental Methodology for Phase I: Study of Commercial Rapid-Setting Materials

Four commercial rapid-setting materials mentioned in Section 3.2.1 were evaluated in Phase I. In the first step of this phase a systematic procedure for estimating the amount of pea gravel and amount of water required to obtain a flowable (minimum slump spread of 482 mm) mixture and to achieve minimum compressive strength of 13.5 MPa at the end of 2 hours was followed. Utilizing the optimum pea gravel content and water content information from Step 1, the behavior of the patching material in fresh and hardened state was tested by varying the temperature of the ingredients in Phase Ib.

3.4.1.1 Phase I, Step 1- Estimation of Pea Gravel and Water Content

For the patching materials which were supplied with pre-mixed aggregates (SET 45, ThoRoc 10-60 and HDBR) mixtures were prepared with variations in pea gravel extension. All the materials in this phase were maintained at room temperature (23°C). The extensions adopted for the patching materials are as below:

1. SET 45 – 40%, 50% AND 60% BY THE MASS OF ONE BAG (22.7 KG)
2. THOROC 10-60 – 50%, 60% AND 80% BY THE MASS OF ONE BAG (22.7 KG)
3. HDBR – 60%, 80% AND 100% BY THE MASS OF ONE BAG (22.7 KG)

The mortar mixer was used for preparing all the mixtures necessary for Phase-I of the project and the mixing sequence was:-

PEA GRAVEL + ¼ WATER-→45 SECONDS OF MIXING → RAPID SETTING CEMENT+ ¾ WATER→ 120 SECONDS MIXING

After mixing was completed, a visual qualitative observation of the mixture was conducted. If any extra amount of water was needed to obtain a spread of minimum 482 mm (see section 3.5) was added and the mixture mixed again for a minute. Extra water was added even if it was not recommended by the manufacturer. The amount of extra water added was fixed at no more than 15% of the water recommended by the manufacturer.

At the end of the mixing process the mixtures were evaluated for flowability using both qualitative and quantitative methods. For qualitative basis, a plexi-glass box with the same dimensions as a typical dowel slot that may be encountered at the construction site, and containing a 1.0 in. diameter dowel bar was prepared. A plexi-glass box was used so that the mixture's ability to flow in the confining space around the dowel bar could be assessed. The concrete was poured in to the box in two layers and vibrated using a vibrator. The concrete was allowed to harden in the box and on demolding the resulting specimen it was checked for voids beneath the dowel bar.

The quantitative analysis for flowability was performed by conducting the slump test within 5 minutes of preparing the mixture. The test procedure adopted is mentioned in detail in section 3.5.1. The mixtures were also cast in cylinders (75 mm diameter and 150 mm long) that were subsequently used for compressive strength. The compressive strength was measured at 1, 3 and 24 hours after casting. For those mixtures which did not set within 30-45 minutes after casting the tests were performed at 2, 4 and 24 h.

For FSHPC mixing which was supplied without any small size aggregate mixture proportions were developed in consultation with the manufacturer. The mixture proportions are given in Table 3.5.

Table 3.5 Mixture proportions for FSHPC

MATERIALS	**QUANTITY (KG/M^3)**
FSHPC	447
PEA GRAVEL	950
SAND	826
WATER	151

The results for all the four materials are discussed in Chapter 4. On the basis of these results a 60 % pea gravel extension was obtained as an optimum content and adopted for all the mixtures performed in Step 2, except for FSHPC. The optimum water content adopted was varying for the different CSRMs and the information is provided in detail in Chapter 4.

3.4.1.2 Phase I, Step 2 – Influence of the Variation in Temperature Conditions of the Materials

After finalizing the pea gravel content, the repair materials were tested for different fresh and hardened concrete properties by varying the temperature of the ingredients. Three different temperature conditions which will cover a broad range of variations in temperature that can possibly occur at a repair construction site were chosen. The temperatures chosen were thus based on criteria that will reflect the minimum possible temperature under which conditions work could be carried out i.e. 10°C. A temperature which will reflect the middle range at which most construction sites operate i.e., 23°C and the maximum temperature at which any construction work could be carried out 40°C. All the mixture ingredients except water were stored for 24 hours at the requisite temperature. For 23 and 40°C conditions mixing water having room temperature (23°C) was used, whereas for 10°C mixing conditions warm water was used. All the mixing was carried out at 23°C and the materials were removed from the stored temperature conditions about five minutes before mixing so that the materials will not have any loss of temperature. The mixing process was carried out at 23°C. After preparation of specimens for testing purpose, the specimens were immediately stored again in the same temperature conditions in which the materials had been stored prior to mixing. The complete process of removal of material from a specific temperature condition, mixing process and preparation of samples was carried out within a total period of 25 ± 5 minutes. The specimens were demolded as per ASTM C 928 after achieving final set and then cured if necessary in moist room at 23°C and 100 percent relative humidity. Only SET 45 was air cured since it had been specifically instructed by the manufacturers.

3.4.2 Experimental Methodology for Phase II- Development of RSSCC

The goal of this phase was to develop rapid setting self-consolidating concrete with cementitious component consisting of portland cement alone or portland cement with pozzolans such as micro-fine flyash (MFA) and silica fume (SF). In Step 1 of Phase-I part of the research plan, optimization of the different ingredients of RSSCC was carried out in detail in six stages. The variables involved in these stages are explained in section 3.4.2.1. In Step 2 of Phase II of the research program, the stability of RSSCC was tested by preparing a total of 26 mixtures. The mixtures were divided in three groups and the variables involved are given in detail in section 3.4.2.2.

3.4.2.1 Phase II, Step 1 - Development of Mixture Proportions for RSSCC

The development of mixture proportions for RSSCC in Phase IIa involved a sequence of six stages shown in Figure 3.7.

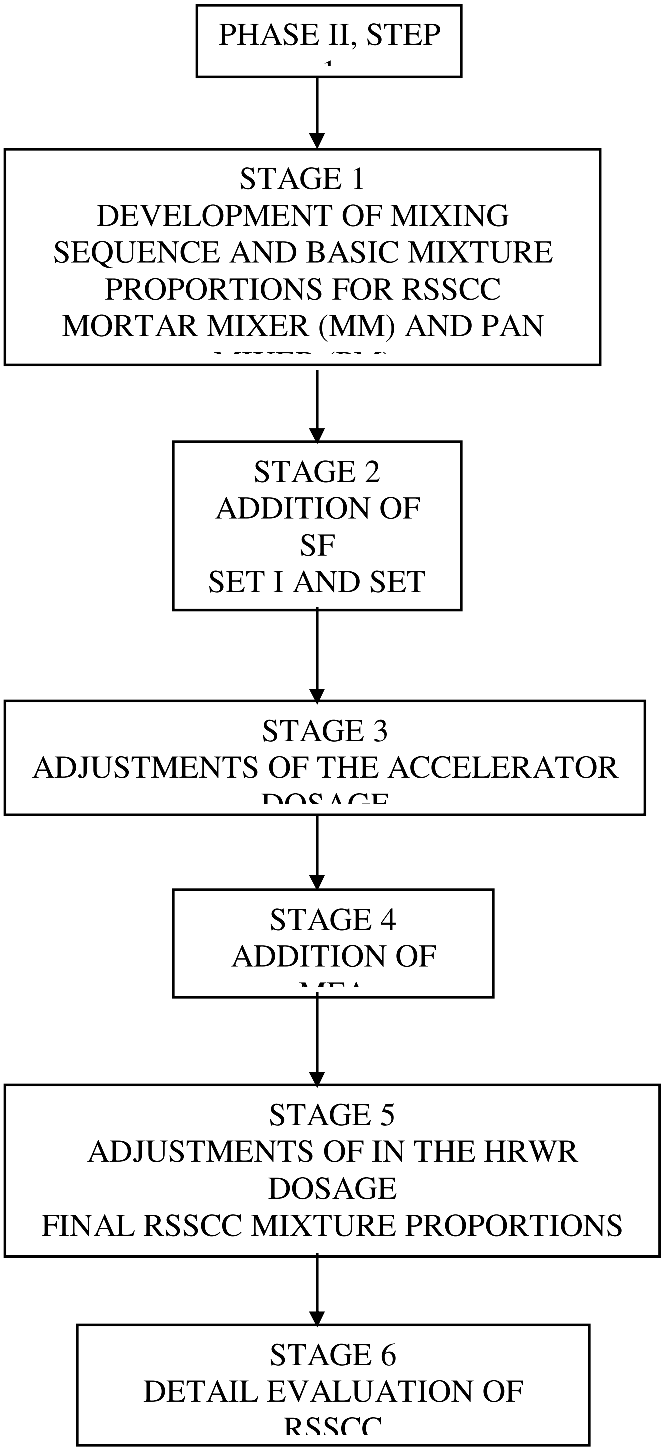


Figure 3.7 Sequence of stages used in development of mixture proportions of RSSCC

Stage 1 of this phase consisted of developing a mixing sequence to be adopted using a mortar mixer to achieve a flowable stable mixture. In the field, mortar mixers are preferred as mixing equipments for repair jobs due to small volume of repair materials and short time span between actual placing and hardening of the mixture. However, published literature as discussed in Chapter 2 shows that pan mixer is most commonly used for producing stable SCC for large volume of materials. It was essential to develop a mixing sequence to produce stable RSSCC. Stage 1 also included development of basic mixture proportions of RSSCC in terms of optimum amount of cement, sand and pea gravel content and water content.

Table 3.6 and Figure 3.8 give detail information regarding the cementitious content, mixing equipment and mixing methodology used in Step 1, Stage 1 of Phase II. Mixtures 1-5, 11-14, 18, 19, 27, and 28 were prepared with portland cement being the only cementitious component. In the rest of the mixtures silica fume was also used as a partial (5 to 10% by mass) replacement for cement. The water-cementitious ratio (w/cm) adopted for the mixtures was varied from 0.3 to 0.5 and the sand to pea gravel ratio in various mixtures was varied from 0.76 to 1.85. Figure 3.9 shows the amount of HRWR and accelerator added to the mixtures. Accelerator was added to Mixes 1 through 10, Mix 11, and Mixes 16 through 19. The details of mixture proportion of all mixtures except Mix 16 and 17 are given in Appendix A.

Table 3.6 Mixing sequence adopted for various mixtures

MIXING METHOD	**MIXING SEQUENCE**	**METHOD OF ADDITION OF HRWR**	**MIX NUMBER**
A (MM)	PEA GRAVEL + WATER* + SAND +AE → 60 S → CEMENT + REST OF WATER → 120 S→ HRWR → 120 S → ACCELERATOR + VMA → 120 S	1-STEP	1, 13, 14
B (MM+PM)	PEA GRAVEL + WATER* + SAND + AE → 60 S → CEMENT + 1/2 WATER+ ½ SP → 120 S→ ¼ WATER + ½ HRWR → 120 S → ACCELERATOR + VMA → 120 S	2-STEP	2, 3, 11, 12, 15[#],18, 19, 20, 21,22[#],23-28
C (MM)	PEA GRAVEL + WATER* → 30 S → SAND+ AE → 60 S → CEMENT + REST OF WATER → 60 S → HRWR → 60 S → ACCELERATOR + VMA → 60 S	1-STEP	4, 5
D (MM)	PEA GRAVEL + WATER* → 30 S → SAND + CEMENT + REST OF WATER + SILICA FUME + 1/2 HRWR → 60 S → 1/2 HRWR →45 S → ACCELERATOR + VMA → 180 S	2-STEP	8, 9[#], 10
E (MM)	PEA GRAVEL + WATER* → 30 S → SAND + CEMENT + REST OF WATER + SILICA FUME → 120 S → HRWR → 60 S → ACCELERATOR → 60 S	1-STEP	6, 7
F (MM)	Pea gravel + water*→ mix for 30 s → Sand + AE + cement + silica fume + MFA + ½ remaining water + ½ HRWR + accelerator→ 45 s → ½ remaining water + ½ HRWR→ 225 s	2-STEP	16
G (MM)	Pea gravel + water*→ mix for 30 s → Sand + AE + cement + silica fume + MFA + remaining water + accelerator→ 45 s → HRWR→ 225 s	1-STEP	17

*NOTE * WATER REQUIRED TO BRING THE PEA GRAVEL TO SSD CONDITION (IF PEA GRAVEL IS NOT IN SSD CONDITION)*

[#]REFER TO FIGURE 3.6 FOR THE TOTAL MIXING TIME OF THESE MIXES

ALL TIMES SHOWN IN THE TABLE ARE MIXING TIMES

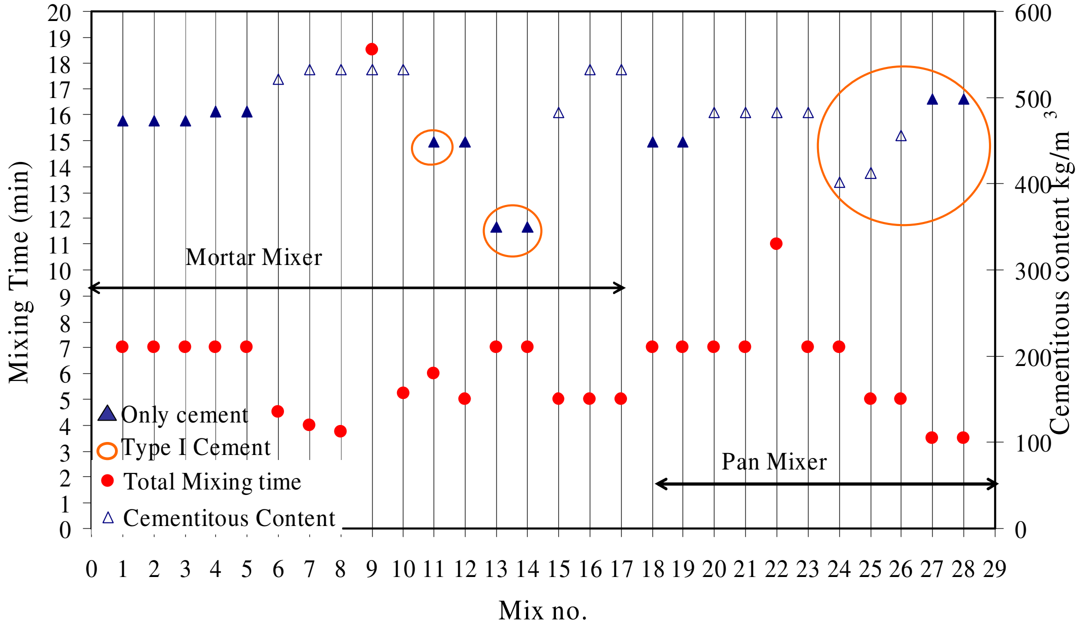


Figure 3.8 Graph of mixing time and cementitious content Vs mix number.

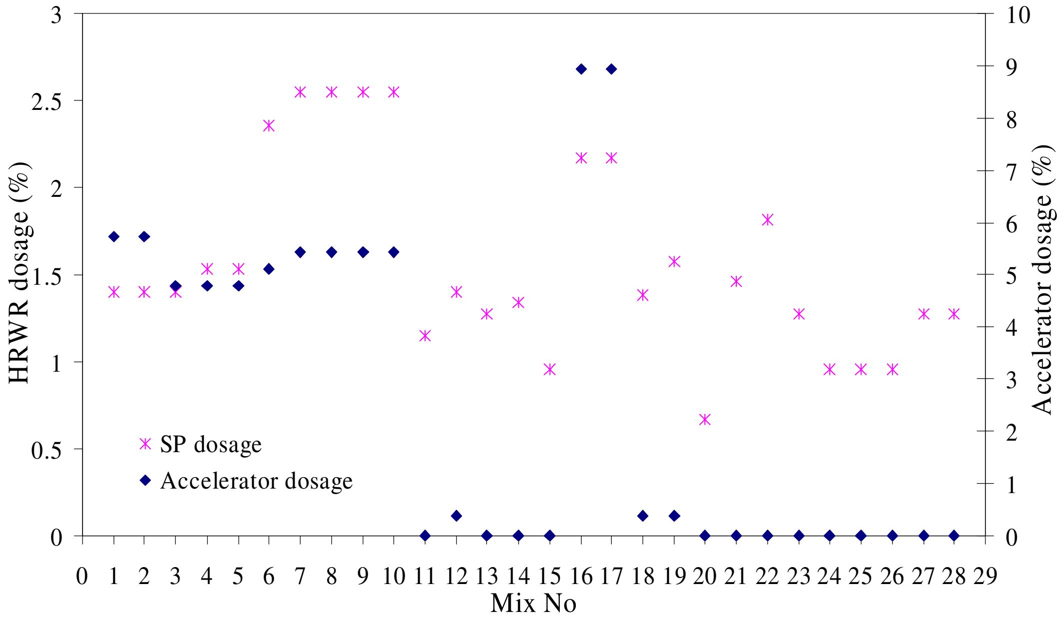


Figure 3.9 HRWR and accelerator dosages for mixtures in Stage 1

The mixtures were prepared using seven different mixing methods (A - G) as listed in Table 3.6. Mixes 1 through 17 were prepared in mortar mixer whereas Mixes 18 through 28 were prepared in the pan mixer (refer to Figure 3.8). The length of mixing period after addition of all HRWR was based on visual assessment of the appearance of the fresh concrete, i.e., the mixture was mixed for a minimum of two minutes after it attained visible flowability in the mixer. The sequence of introduction of HRWR is termed either as 1-Step or 2-Step process, depending upon the amount added in each step. If the entire amount of superplasticizer was added at one time after all the cement and mixing water have been added (mixing methods A, C and E) then this process was called 1-Step addition. If the total HRWR dosage was split in two equal parts, with one half added with the cement and half added later with the remaining portion of the water (mixing method B and D), this process was called 2-Step addition. Mixtures 16 and 17 were carried out at the end of Stage 6 but are included in the group of mixtures discussed in connection with Stage 1 as they were used to confirm the superiority of the 2-Step process of HRWR addition. These mixtures were prepared to emphasize the benefits of the 2-Step process. The mixture proportions for these two mixtures are same as the final mixture proportions of RSSCC shown in Table 3.10.

The basic mixture proportions developed from Stage 1 based on results in Chapter 5 are given in Table 3.7. The 2-Step process of HRWR addition (mixing Method F) was found to be most suitable to achieve self-consolidating properties and hence was adopted for all further stages (Stage 2 to Stage 6) of the project.

Table 3.7 Basic mixture proportions derived from Stage 1

MATERIALS	QUANTITY
CEMENT (KG/M3)	485
WATER (KG/M3)	160
PEA GRAVEL (KG/M3)	578
SAND (KG/M3)	1105
ACCELERATOR % (BY MASS OF CEMENT)	3.25
AEA % (BY MASS OF CEMENT)	0.02
HRWR % (BY MASS OF CEMENT)	1.3
W/CM	0.33

In Stage 2, the basic proportions of RSSCC listed in Table 3.7 were altered by adding varying amounts of densified silica fume (SF). The amounts of SF added were 0, 5, 7.5 and 10 percent by weight of cement. A total of eight mixtures were produced in Stage 2. Although for each of the mixtures the total design water content was kept constant at 160 kg/m^3, the actual amount of water added varied, depending upon the moisture content of aggregates. The moisture content of all aggregates used in Stage 2 mixtures was below that required for SSD condition. However, the relative differences between the actual and the SSD moisture content varied, giving rise to two SETS of mixtures as shown in Table 3.8.

The aggregate used in SET I mixtures was relatively wet and the amount of "extra" water added during mixing (to compensate for absorption) varied from 0 to 16 kg/m^3 (see Table 3.8). The aggregate used in SET II mixtures was drier than that used in SET I mixtures and, as a result, the amount of water added to compensate for absorption varied from 10 to 25 kg/m^3 as shown in Table 3.8. The fine aggregate to coarse aggregate volume was varied from 1.79 to 1.86, to account for the changes in silica fume content of the mixture. The HRWR dosage was kept constant for all mixtures at 3.25% by mass of cement.

SET	**Mixture #**	**SF %**	**Cement (kg/m^3)**	**Pea gravel (kg/m^3)**	**Sand (kg/m^3)**	**Extra water added (kg/m^3)**	**% HRWR (by weight of cement)**
SET I	1	0	485	604	1118	16	1.38
	2	5	485	576	1042	0	1.76
	3	7.5	485	569	1028	1	1.88
	4*	10	485	561	1018	11	2.00
SET II	5	0	485	597	1112	22	1.38
	6	5	485	568	1035	15	1.76
	7	7.5	485	558	1029	10	1.88
	8	10	485	555	1010	25	2.00

Table 3.8 Mixture Composition of concrete produced during Stage II of design process

Design water content = 160 kg/m^3 (assuming aggregate in SSD condition)
*Note - * mixture selected for Stage 3 experiments*

Based on the fresh and hardened properties obtained (see details in Chapter 5) mixture #4 from (SET I) was selected for further development in Stage 3 as its properties were closest to the desired target values.

Stage 3 in the mixture development process involved varying the accelerator dosage from 4.7 % by weight of cement to 9.1% by weight of cement (485 kg/m^3) to obtain the optimum quantity of accelerator required to achieve target compressive strength at 6 h. In this Stage, a total of seven mixtures were produced of which the first five mixtures had constant HRWR dosage (2.5% by weight of cement). In the last two mixtures, the HRWR dosage was reduced to 2% by weight of cement. The mixture with 2% HRWR and 8.8% of accelerator dosage by weight of cement was adopted for further development in Step 4 of the mixture design process.

Stage 4 involved addition of micro-fine fly ash to the mixtures that contained 7.5 and 10%, respectively of SF (see Table 3.9). The mixture proportions used were similar to those of SET I # 3 and SET I # 4 mixtures, except for some adjustments in the HRWR dosage to maintain required flowability upon addition of MFA. A total of two mixtures were prepared during this Step, of which Mixture # 2 was used in Step 4 of the mixture design process.

Table 3.9 Mixture proportions for Stage 4 mixtures

Material	**Mixture 1**	**Mixture 2**
Cement (kg/m^3)	485	485
Micro-fine fly ash by weight of cement (%)	10	7.5
Silica fume by weight of cement (%)	7.5	10
w/cm	0.311	0.311
HRWR dosage (% by weight of cement)	1.75	2.0
Water (kg/m^3)	176	176
Pea gravel (kg/m^3)	554	551
Sand (kg/m^3)	964	928

In Stage 5, the HRWR dosage was varied between 1.88 to 2.51% by weight of cement to determine the optimum dosage with respect to flow and segregation characteristics. Five mixtures were prepared and the mixture containing 2.15% of HRWR by weight of cement was selected as a basis for the final RSSCC mixture proportions. These final proportions are given in Table 3.10.

Table 3.10 Mixture proportion for RSSCC

Material	**Quantity**
Cement (kg/m^3)	485
Micro-fine fly ash by weight of cement (%)	7.5
Silica fume by weight of cement (%)	10
w/cm	0.311
HRWR dosage (% by weight of cement)	2.15
Accelerator (% by weight of cement)	8.88
Pea Gravel (kg/m^3)	581
Sand (kg/m^3)	928
Water (kg/m^3)	176

In Stage 6 specimens were prepared using the final RSSCC mixture proportions to carry out various tests to determine different properties such as rate of compressive strength gain, freezing and thawing durability, slant shear bond strength, permeability to chloride ions, drying shrinkage and cracking potential.

3.4.2.2 Phase II, Step 2 – Evaluation of Sensitivity of RSSCC to Production Variables

The production variables chosen for study in this stage are shown in Figure 3.9 and were classified in three groups as follows:

1. VARIATION IN AGGREGATE MOISTURE CONTENT AND TYPE OF MIXING EQUIPMENT
2. VARIATION IN AGGREGATE GRADATION

3. REMIXING OF MIXTURE AT DIFFERENT TIME INTERVALS

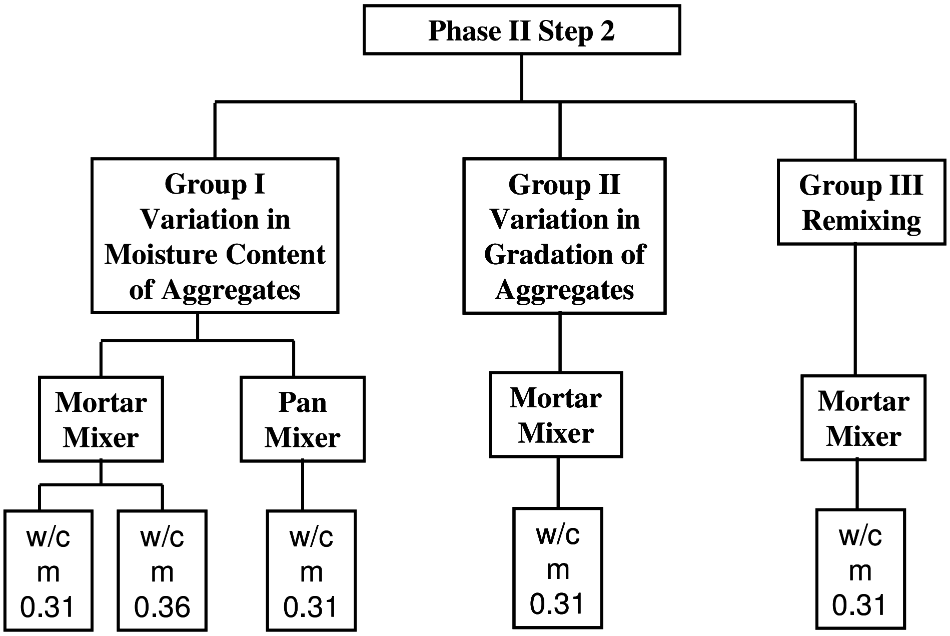


Figure 3.9 Schematic of experimental variables adopted for Phase IIb

A total of 25 different mixtures were prepared and tested during the study (in reality 27 mixtures were prepared but one of them (mortar mixer Sand-1 and PG-1) was common to all the three groups. Group I mixtures were prepared in two types of mixers: mortar mixer and pan mixer. For this group of mixtures, two water-cementitious material ratios (0.31 and 0.36) were used in the mortar mixer whereas one w/cm value (0.31) was used in the pan mixer. All Group I and Group III mixtures were prepared using Sand-1 and PG-1. In preparing Group I mixtures in the mortar mixer, the moisture content of both Sand-1 and PG-1 was varied from dry condition (0% moisture) to twice the moisture needed to achieve SSD condition, (2 x SSD), in steps of 0.5 x SSD. As a result, for each of the two w/cm values five different mixtures were prepared with aggregate moisture content of 0%, 0.5 x SSD, 1.0 x SSD, 1.5 X SSD and 2.0 x SSD, respectively. When preparing Group I mixtures in the *pan mixer* the aggregate moisture content used was 0%, 1.0 x SSD and 2.0 x SSD, thus resulting in three different mixtures. In Group III, mixtures were made in the mortar mixer. In preparing Group III mixtures the mixtures were remixed after a rest time (after completing the initial mixing process as per Method F in Table 3.6) in steps of 10, 17 and 25 minutes. The mixtures were stored in the mixer during the rest period. The mixtures were remixed for 60 seconds.

Table 3.11 gives the mixture proportions for Group I concretes. These proportions were developed assuming that all aggregates will be in SSD conditions and that the mixtures will have 6.5% of entrained air. The cementitious content in all mixtures was kept constant at 570 kg/m^3. For mixtures prepared with w/cm = 0.31 the design water content was 176 kg/m^3, total volume of aggregate in the mixture was about 57% and the volume of fine aggregate as percentage of total aggregate volume was about 63%. For mixtures prepared with w/cm of 0.36, the design water content was 205 kg/m^3, total aggregate volume was 54% and fine aggregate volume as percentage of total aggregate volume was 65%. In this study water to cementitious ratio is defined as the design amount of water divided by the total cementitious content assuming the aggregates to be in SSD condition. The *free water to cementitious ratio (free w/cm)* is defined as the ratio of actual water added to the mixture (accounting for the moisture condition of the aggregates) to the total cementitious content. When batching the mixtures, the water content of the different chemical admixtures used for preparing RSSCC was subtracted from the total (design amount) of water (assuming the aggregate in SSD condition). As a result, the water quantities given in Table 3.11are lower than the design values discussed above.

Table 3.11 Mixture proportions for Group I concretes

MATERIALS	**QUANTITY FOR W/CM 0.31 (KG/M^3)**	**QUANTITY FOR W/CM 0.36 (KG/M^3)**
CEMENT	485	485
SILICA FUME	48.5	48.5
MICRO FINE FLY ASH	36.5	36.5
PEA GRAVEL	581	510
SAND	928	923
HRWR	10.5	8.8
AIR ENTRAINING AGENT	0.17	0.22
ACCELERATOR	43.3	43.3
WATER	134	164

Table 3.12 gives information about the combination of aggregate gradations adopted for Group II mixtures. In all, six different mixtures were produced. Three of these mixtures contained PG-1 coarse aggregate but each was prepared with different sands (Sand-1 through Sand-3). For the other three mixtures, the source of fine aggregate was kept constant (Sand-1) but the coarse aggregate was varied (PG-2 to PG-4). These mixtures were prepared in the mortar mixer.

Table 3.12 Combination of aggregates used for Group II mixtures

SAND	**PG-1**	**PG-2**	**PG-3**	**PG-4**
SAND-1	√*	√	√*	√*
SAND-2	√	---	---	---
SAND-3	√	---	---	---

**NOTE-MIXTURE PROPORTIONS AS LISTED IN TABLE 1 FOR W/CM=0.31*

In Group II mixtures the same general mixture proportions as those used for Group I mixtures with w/cm of 0.31 (with slight variations due to change in specific gravity of aggregates) were prepared. The mixture proportions adopted are shown in Table 3.13. All aggregates used in Group II mixtures were in SSD condition. As mentioned earlier, the water added as a part of the chemical admixtures was accounted for and subtracted from the total (design) water content.

Table 3.13 Mixture proportions for Group II mixtures

MATERIALS	**QUANTITY FOR SAND- 1 AND PG-2 (KG/M^3)**	**QUANTITY FOR SAND-2 AND PG-1 (KG/M^3)**	**QUANTITY FOR SAND- 3 AND PG-1 (KG/M^3)**
CEMENT	485	485	485
SILICA FUME	48.5	48.5	48.5
MICRO FINE FLY ASH	36.5	36.5	36.5
PEA GRAVEL	577	582	582
SAND	929	954	936
HRWR	10.5	10.5	10.5
AIR ENTRAINING AGENT	0.17	0.17	0.17
ACCELERATOR	43.3	43.3	43.3
WATER	134	134	134

For Group III mixtures the mixture proportions adopted for Group I mixtures with w/cm of 0.31 were used.

3.5 Test Procedures and Requirements

Based on the literature review and evaluation of the specifications and approved patching materials for Dowel Bar Retrofit projects of various state DOTs, the following properties were selected as the key properties of the repair material that influence the long term performance of rapid-setting repair materials:

1. SETTING TIME,
2. FLOWABILITY AND FILLING ABILITY,
3. RATE OF STRENGTH GAIN,
4. FREEZE-THAW DURABILITY,
5. DRYING SHRINKAGE,
6. CRACKING POTENTIAL, AND
7. BOND STRENGTH.

In this section the test procedures for measuring different fresh and hardened concrete properties, deviation from approved test procedures if any, changes in curing regimes in comparison to those listed in relevant standards, requirements established for different tests, are specified in detail for Phase I and Phase II of the research program. For all hardened concrete properties except air content, three samples were prepared and tested. The average values are reported.

3.5.1 Slump and Slump Flow

The workability was measured in terms of slump or spread of the concrete patty and the test was conducted as per ASTM C 143 for Phase I mixtures For Phase I mixtures the slump requirements as per ASTM C 928 is 75 mm (refer to Table 3.14). But this requirement was changed for this research project to a requirement of minimum of flow of 482 mm. To measure the flow, after completion of rodding the concrete in the slump cone in three layers, the slump cone was lifted, and the concrete was allowed to flow. The slump was measured as the horizontal spread (diameter) as opposed to the vertical height for normal concrete and reported as the “spread of the concrete”. In Phase I mixtures, only the spread was measured for all the mixtures except for ThoRoc^{TM}10-60 cast with materials at 40°C.

For Phase II mixtures the workability was measured as slump flow and the test was conducted as per ASTM C 1611. In this test unlike ASTM C 143 no rodding in three layers is carried out and the horizontal spread is measured and reported as the slump flow. For Phase II mixtures, the T_{50} flow time and the Visual Stability Index (VSI) were also described for the same slump flow patty as per ASTM C 1611. The time taken by the slump flow patty to flow 500 mm is termed as T_{50} flow time and is expressed in seconds. The VSI is an index (as per ASTM C 1611) to describe the distribution of coarse aggregate within the concrete mass, distribution of the mortar fraction along the perimeter of the slump flow patty and the bleeding characteristics of the slump flow patty. A VSI of 0, which indicates a stable non-segregating and non-bleeding concrete, was the target index for this study.

3.5.2 V-Funnel and L-Box

The V-funnel test is a simple test where the concrete is allowed to flow from a funnel of standard dimensions (as shown in Figure 3.10) under its own weight (Jin & Domone, 2002). The flow time is defined as the time between the start of the flow and daylight being first visible when looking vertically down through the funnel. To conduct the test, all the inside surfaces of the V-funnel were first dampened using a moist cloth. The bottom gate was closed and concrete poured into the funnel, without disturbing the poured concrete by rodding or vibration. After a delay of about 10±2 s the gate was opened and the concrete was allowed to flow into a container (The European Guidelines for Self-Compacting Concrete, 2005). The V-funnel flow time was measured to the nearest 0.1 s.

L-box test method uses a test apparatus comprising of a vertical section and a horizontal trough into which the concrete is allowed to flow (on the release of a trap-door) from the vertical section while passing through reinforcing bars placed at the intersection of the two sections of the apparatus (see Figure 3.11). To conduct the test, the trap door between the horizontal and the vertical section was closed. The inner surfaces of the L-box apparatus were dampened with a moist cloth. The concrete was poured into the vertical arm of the box and allowed to stand for about one minute. After which the trap door was opened and the concrete was allowed to flow from the vertical section into the horizontal trough of the L-box. After all the movement of the concrete has occurred, the height of the concrete at the beginning of the horizontal section (H_1) and that at the end of horizontal section (H_2) were measured. The L-box test can give an indication as to the filling ability and passing ability of the SCC mixture. The passing ability (PA) is calculated from the following equation:

$$PA = H_2 / H_1 \qquad \text{Equation 3.1}$$

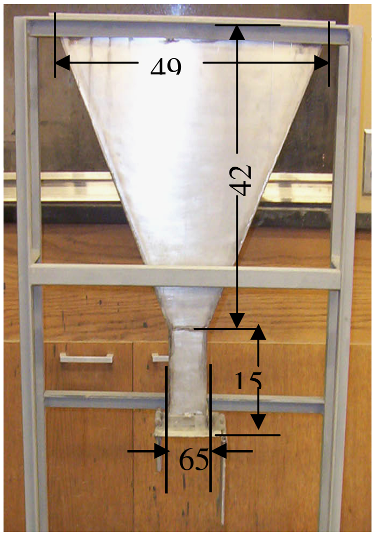


FIGURE 3.10 V- Funnel Test Apparatus
Note: All dimensions are in mm

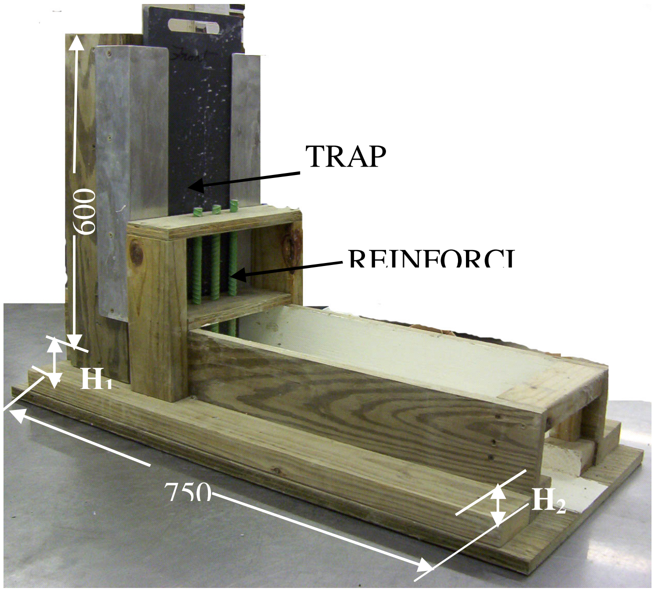


FIGURE 3.11 L - Box Test Apparatus

3.5.3 Setting Time

Setting time was carried out as per ASTM C 266 for Phase I mixtures whereas ASTM C 403 was implemented for Phase II mixtures. For all the RSSCC mixtures prepared in Phase II the concrete was not sieved through sieve size 4.75 mm. Placement of concrete in test container was done without subjecting the concrete to any tapping or rodding. The first measurement was performed within 20 minutes of addition of water to the mixture.

3.5.4 Air Content

The air content of fresh concrete was measured as per ASTM C 231 for Phase II mixtures. While pouring the concrete in the test apparatus no tapping or rodding was carried out during the testing process for Phase II mixtures.

Air content of hardened concrete was carried out as per ASTM C 457. Hardened concrete samples were sawed and polished before conducting the test.

3.5.5 Compressive Strength and Slant Shear Bond Strength

The compressive strength test was performed as per ASTM C 39 by casting samples in cylinder of 75 mm diameter and 150 mm long. For Phase I mixtures, the samples were prepared in three layers and vibrated using the vibrating table as per ASTM C 39. Immediately after casting, the specimens were placed in a room kept at the same temperature as that of the ingredients prior to the mixing process (10, 23 or 40° C). Those specimens which were to be tested at 1 h or 2 h were removed from the room, demolded and tested at room temperature. The other specimens were demolded at 3 h after addition of water and were placed in the moist room at 23°C and 100% relative humidity (RH). For SET®45R and HW, the samples were air-cured. The samples were tested at the age of 1 h or 2 h, 3 h or 4 h, 24 h and 672 h (28 days) for Phase I mixtures. The actual time of test depended upon the setting time and the variabilities under consideration.

For Phase II mixtures, the samples were prepared in three layers but were not rodded or vibrated. The samples were then sealed and placed at 23°C till the end of 6 h, after addition of water to the ingredients. They were then demolded and stored in moist room at 23°C and 100% RH. The compressive strength test was carried out at 6 h, 8 h and 24 h for Phase II mixtures.

The slant shear bond strength was performed on 3x6 in cylinder specimens as per ASTM C 882 but was modified as per ASTM C 928. The mortar specimens on which the repair concrete was placed was prepared as per ASTM C 109 using Type III cement and were moist cured for 28 days after which the repair concrete was bonded to it. No bonding agent was applied to the mortar surface.

3.5.6 Drying Shrinkage and Cracking Potential

The drying shrinkage of the different repair materials was measured as per ASTM C 157. Prism samples of 75 mm cross section and 285 mm long were cast for Phase I mixtures in three layers and vibrated. The samples were then placed immediately in the respective temperature conditions for Phase I Step 2 mixtures (10, 23 or 40° C). The specimens were demolded at age recommended by ASTM C 928 (3 h after addition of water). The first measurements for drying shrinkage were performed at the age of 3 h after addition of mixing water. The samples were then returned to the same temperature conditions at which they were kept initially (10, 23 or 40° C) and remained at these conditions till the end of experiment. The relative humidity for the different temperature conditions varied and was 50 % for 40 and 23° C and 90 % for 10°C.

For Phase II mixtures, the same regime for preparation of sample and storage of samples as described in the earlier paragraph was followed; except, while preparing the samples, the concrete was not vibrated or rodded. Also, demolding was carried out 6 h after addition of water.

Cracking potential of the repair materials was determined by performing the restrained ring test as per ASTM C 1581. This test was performed only at 23°C ambient temperature condition. The sample preparation and demolding regime adopted was same as that for drying shrinkage for the respective phases. Four strain gages were attached to the steel ring and the average of the four reported as the strain present in the specimen. The strain information was collected using a data logger. The strain data collection was started within 20 minutes of addition of mixing water.

3.5.7 Freeze-Thaw Durability

Freezing and thawing studies on repair materials was carried by subjecting the concrete samples to rapid freezing and thawing in water as per ASTM C 666 Procedure A. The specimens were demolded after 2½ to 2¾ h after addition of water in case of Phase I Step 2, mixtures and cured at 23°C and 100% RH for 14 days. SET 45 ® R and HW were air cured for 14 days and were then placed in water for 24 h before the start of the freezing and thawing process. Incase of Phase II Step 1 mixtures, the specimens were demolded at the end of 6 h after addition of water and then placed in moist room for curing for 14 days.

3.5.8 Test Requirements

To develop the test requirements for Phase I of the research, the test specifications and requirements of various DOTs and data sheets of the selected materials were studied. (Refer Appendix D for data sheets of the CSRMs used in the study) Table 3.14 gives the requirements developed after the studying the available literature. The requirements given in Table 3.14 are for mixes cast at 23°C and those for mixtures cast with materials at 10°C and 40°C were not developed.

Table 3.14 Test specifications and requirements for Phase I

PROPERTY	**TEST METHOD**	**REQUIREMENTS**	
		PROJECT SPECIFIED	**AS PER ASTM C 928**
SLUMP	ASTM C 143	480 MM (SLUMP SPREAD)	75 MM
SETTING TIME	ASTM C 266 (GILMORE)		
INITIAL SETTING TIME		10-20 MIN	--
FINAL SETTING TIME		12-35 MIN	--
COMPRESSIVE STRENGTH	ASTM C 39		
1 H		13.8MPA (2000PSI)	--
2 H		13.8MPA (2000PSI)	--
3 H / 4H		21 MPA (3000PSI)	21 MPA
24 H		27.5MPA (4000PSI)	35 MPA (5000PSI)
28 DAY		35MPA (5000PSI)	35 MPA
BOND STRENGTH	ASTM C 882 MODIFIED BY ASTM C 928		
1 DAY		7MPA (1000PSI)	7 MPA (1000PSI)
7 DAY		10MPA (1500PSI)	10MPA (1500PSI)
LENGTH CHANGE IN AIR	ASTM C 157 MODIFIED BY ASTM C 928	MAX -0.15%	MAX -0.15%
FREEZE THAW RESISTANCE PROCEDURE A	ASTM C 666	NOT LESS THAN 60 % AT 300 CYCLES	OPTIONAL

The target values for different properties of the rapid-setting self-consolidating concrete prepared in Step 1 of Phase II were as follows:

- Slump flow – 660 mm
- Visual Stability Index - 0

- L-box passing ratio - not less than 0.75
- Air Content – 6%
- Final Setting Time (FST) – less than 3 hours
- Compressive strength at 6 hours – 17 MPa
- Chloride permeability at 28 days – less than 1200 coulombs
- Freezing and thawing resistance – Durability factor higher than 60% at the end of 300 cycles (as per ASTM C 666)
- Slant shear bond strength at 1 and 7 days – 10 and 17 MPa, respectively (as per ASTM C 928)

For Step 2 of Phase II, the fresh concrete properties measured were slump flow, flow time for the concrete patty to flow a distance of 500 mm (T_{50}), visual stability index (VSI), V-funnel flow time and the passing ratio (using L-box test).

Using the recommendations of ASTM C 1611 for single operator precision, the acceptable value of slump flow was fixed at ± 25 mm of the value obtained for the mixture having aggregates in SSD condition for both w/cm. For this study the acceptable value of T_{50} was fixed at ± 2 of the value obtained for the mixture having aggregates in SSD condition for both the w/cm. This value is slightly above the repeatability value of 1.18 s reported in the European Guidelines for SCC. A VSI of zero, which indicates a stable non-segregating and non-bleeding concrete, was the target index for this study.

As per the European Guidelines for SCC, the acceptable variation for repeatability for V-funnel flow time of 8 s is 2 s whereas for 15 s it is 4.4 s. For this study, the average of these two values (±3.1 s) was considered as the acceptable deviation of V-funnel flow time from the value obtained for the mixture having aggregates in SSD condition for both w/cm. The acceptable value for the L-box test was ± 0.05 of the value obtained for the mixture having aggregates in SSD condition for both w/cm. Both of these values are within the repeatability ranges reported by the European Guidelines for SCC.

The acceptable value for compressive strength was deviation of ± 2 MPa from the strength obtained for mixture having aggregates in SSD condition. The adopted deviation constituted about ± 10 % of the ultimate strength at 6 h.

CHAPTER 4: TEST RESULTS FOR PHASE – I STUDY OF COMMERCIAL RAPID-SETTING MATERIALS

4.1 Introduction

In this chapter, the test results for the four commercial repair materials tested during Phase I are presented. Sections 4.2 through 4.5 include details on Step 1 – mixture proportioning (determination of the optimum amount of pea gravel extension) and Step - 2 test results for each of the commercial materials used in this study. For each materials, the test results for fresh concrete properties (slump flow and setting time) and hardened concrete properties (compressive strength, slant shear bond strength, shrinkage and resistance to freeze-thaw cycles) are presented. Section 4.6 deals with an in-depth analysis of the CSRMs in comparison with each other when prepared with materials pre-conditioned to different temperature.

4.2 SET 45 (Regular and Hot Weather)

As indicated in section 3.2 of Chapter 3, SET®45 is available in two formulations, regular and hot weather. While preparing mixtures for estimation of pea gravel content and water content (Phase I, Step 1) only SET®45R was adopted. SET ®45 HW was only used during Step 2 to produce mixtures for which the materials were pre-conditioned to 40°C. The amount of pea gravel extension used for SET® 45HW mixture was the same as that adopted for SET®45R.

4.2.1 Step 1- Mixture Proportioning (Estimation of Percent Aggregate Extension and Water Content for SET®45R Mixtures)

The manufacturer supplied dry SET®45R mortar was extended by adding 40, 50 and 60 percent of pea gravel by weight of original dry material. It was observed that mixture containing 40 % pea gravel required about 0.20 L of extra water (above the supplier's recommendation) per bag (22.7 kg) of dry SET®45R to achieve adequate cohesiveness. Though the mix appeared to be cohesive, voids were formed beneath the dowel bar when the mix was placed in the plexi-glass box that was used to stimulate the typical dowel bar installation slot (see Figure 4.1).

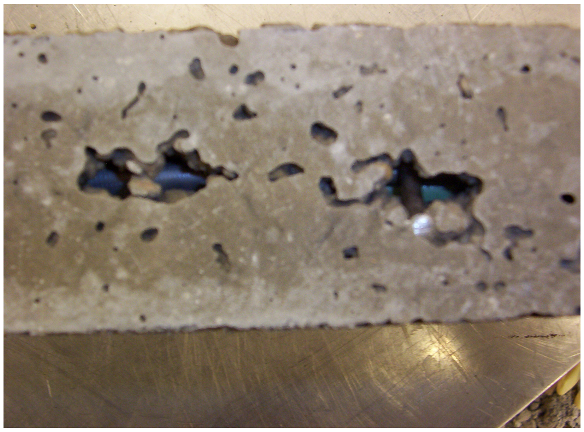


Figure 4.1 Voids formed below the dowel bar in SET®45 R with 40 % of pea gravel extension

Mixture cast with 50 % of pea gravel extension required 0.16 L of extra water to achieve a cohesive mix as well as good flowability. Mixture prepared with 60% of pea gravel extension required 0.15 L of extra water. Formation of any voids was not observed when this mixture was placed in the plexi-glass box. Due to its cohesiveness and flowability, the mixture was able to flow underneath the dowel bar completely.

Figure 4.2 shows a plot of the average compressive strength of SET®45 R at various ages for all the aggregate extension levels used. The difference in average compressive strengths is less than 2 MPa for all the pea gravel extensions but is always higher for the mixture containing 60% pea gravel extension. Due to its ability to form a cohesive flowable concrete and high compressive strength, pea gravel extension 60% was adopted for performing the Phase 1, Step 2 testing using SET®45 R.

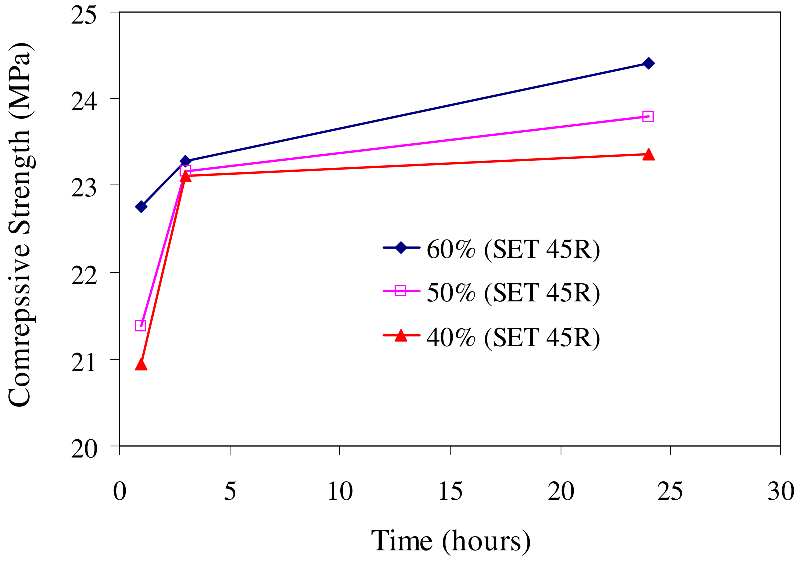


Figure 4.2 Development of compressive strength with different pea gravel extension using SET$^{®}$45 R

4.2.2 Step 2: Evaluation of the effect of initial material temperature for SET 45®R and SET 45®HW

The ingredients for the mixtures prepared in this section were stored at different temperature conditions (10, 23 and 40°C) for 24 h prior to the mixing process as discussed in the section 3.4. The mixing process was carried out at 23°C. Table 4.1 shows the spread of the mixtures prepared with materials at various temperatures. The mixture cast with materials at 40°C required the highest amount of additional water (0.23 L) to obtain the desired spread of more than 482 mm mixture. The slump flow obtained for 40oC condition is also the highest amongst all of the temperature conditions (508 mm). The additional water required for mixtures cast with materials at 23°C and 10°C is o.15 L respectively. Figure 4.3 shows a picture of the spread obtained by the slump test for mix cast with materials (SET 45®R) at 23°C.

Table 4.1 Workability parameter of SET 45®mixtures cast with materials at different temperatures

MATERIAL	MATERIAL TEMPERATURE (^{O}C)	WORKABILITY PARAMETERS (MM)	EXTRA WATER ADDED (L)
SET 45®R	10	457	0.15
	23	482	0.15
SET 45®HW	40	508	0.23

Figure 4.3 Spread as a workability parameter for SET ®45R with 60% pea gravel extension at 23°C

The initial setting time of SET®45 for materials stored at different temperature are fairly low and ranges from 11 to 16 minutes (refer to Table 4.2). The highest initial and final setting time was observed for SET 45®HW.

Table 4.2 Setting time SET 45®mixtures cast with materials at different temperatures

MATERIAL	**MATERIAL TEMPERATURE (°C)**	**SETTING TIME**	
		INITIAL SETTING TIME (MINUTES)	**FINAL SETTING TIME (MINUTES)**
SET 45®R	10	14	25
	23	11	22
SET 45®HW	40	16	28

The average compressive strength at various ages for mixtures cast with materials stored at different temperatures is shown in Figure 4.4. As mentioned earlier, SET®45 R was used for mixtures with materials at 10 and 23°C and SET®45 HW was used for mixture with materials at 40°C.

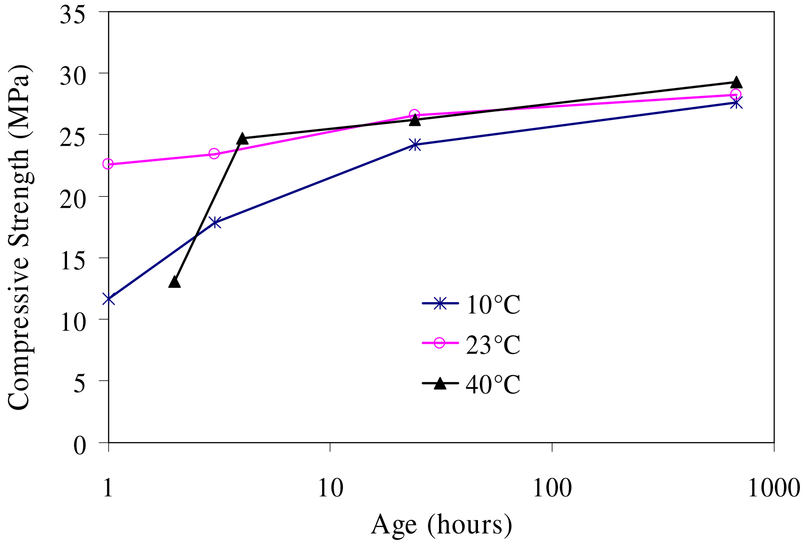
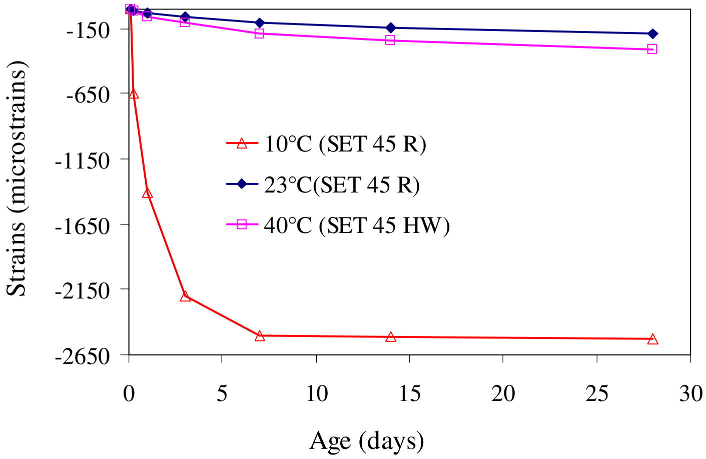


Figure 4.4 Compressive Strength of SET 45® mixtures (R and HW formulations) cast with materials at different temperatures

The cylinder specimens of the mixture cast with materials at 40°C could not be demolded within one hour whereas those cast with materials at 23 and 10°C were demolded within 1 hour and tested. Mixture cast with SET®45 R material at 23°C gained 90% of its strength within the first hour and the curve reaches a plateau after 24 hours. The average compressive strength of mixtures cast with materials at 40°C is 13 MPa at the age of 2 hours and the plot shows a rapid increase of strength (25 MPa) at the end of 4 hours. Lower compressive strength values at the initial ages for mixture cast with materials at 40°C can be attributed to presence of retarders in the formulation of SET 45® HW. The mixture cast with materials at 10°C has the lowest strength amongst all conditions at all ages. At the end of 672 hours (28 days) all the mixtures achieved comparable compressive strength. However, none of the mixtures were able to achieve the required compressive strength of 35 MPa at the end of 28 days as stipulated in section 3.5.8 of Chapter 3.

The drying shrinkage over a period of 28 days for mixtures cast with materials at different temperatures for SET 45® shown in Figure 4.5. The drying shrinkage is low for mixtures cast with materials at 23°C and 40°C and is 190 µm and 250 µm, respectively, at the end of 28 days. The drying shrinkage value of 2650 µm for mixtures cast with materials at 10°C is the highest amongst the three temperature conditions.

Figure 4.5 Drying shrinkage of SET ®45 mixtures (R and HW formulations) cast with materials at different temperatures



The same samples show a different behavior when the weight change values are considered. The samples cast with materials at 23oC and 40°C show a weight loss of about 1% and 2.25 %, respectively, at the end of 28 days as shown in Figure 4.6. Samples of mixtures cast with materials at 10°C show a weight loss of about 1.0% at the end of 28 days. SET 45® is a phosphate based material with high amount of magnesium oxide and phosphoric acid. The high shrinkage strains for mixture made with materials at 10°C and stored in 90% RH can be due to the moisture provided by the environment which could be causing an adverse reaction in the concrete at 10°C. As per the manufacturer's data sheet (see Appendix D) SET 45® should not be water cured.

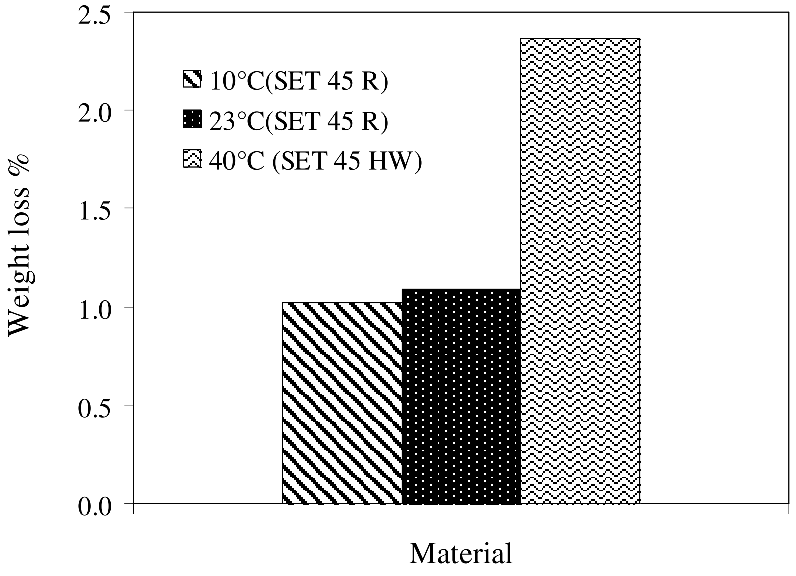


Figure 4.6 The 28-day weight change for SET 45®mixtures cast and cured with materials at different temperature

Figure 4.7 Specimen of SET®45 prepared with materials at 23°C at the end of 300 cycles of freezing and thawing

Figure 4.7 is a picture of a sample cast with materials at 23°C and subjected to 300 cycles of freezing and thawing. It can be observed that most of the surface paste is lost due to scaling and that the aggregates are exposed.

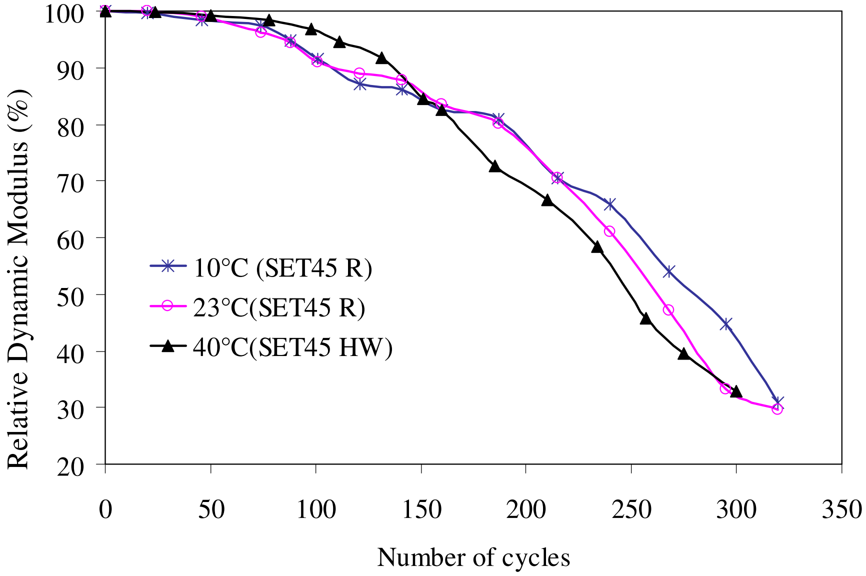


Figure 4.8 Loss of relative dynamic modulus of elasticity over 300 cycles of freezing and thawing for SET ®45 mixtures cast with materials at different temperatures

The loss of relative dynamic modulus at the end of 300 cycles is about 70 percent for all mixtures tested (see Figure 4.8). The loss of dynamic modulus for mixtures cast with materials at 40°C is about 8% up to 130 cycles but increases sharply thereafter as the number of cycles are increased. The loss of dynamic modulus for mixtures prepared with materials at 10°C and 23°C is about 2% till 75 cycles after which the rate of decrease in relative modulus increases gradually.

Figure 4.9 shows the cumulative weight loss for specimens that were subjected to freezing and thawing cycles. The trend of the weight loss is very similar to the observed for dynamic modulus of elasticity with specimens prepared with materials at 40°C experiencing highest total weight loss (125 g) at the end of 300 cycles. The specimens cast with materials at 10°C have the lowest weight loss of about 85 g. The rate of weight loss increases after 130 cycles for mixture cast with material at 40°C (Figure 4.9), which and corresponds well to the loss in dynamic modulus for these samples discussed earlier.

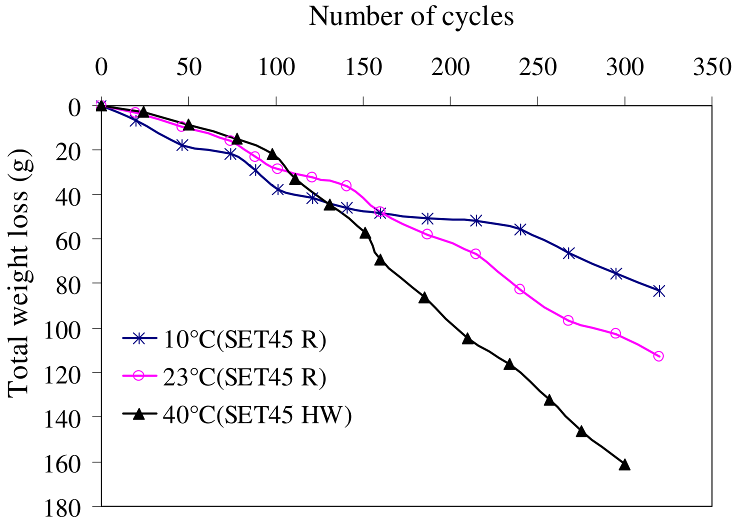


Figure 4.9 Weight loss over 300 cycles of freezing and thawing for SET 45®mixtures cast with materials at different temperatures

Slant shear bond strength test was carried out as per ASTM C 928 at the age of 1 and 7 days. Figure 4.10 gives the bond strength values at these two ages for various initial temperatures of SET®.45 materials. It can be seen that differences in the initial temperature conditions of the materials did not result in any significant variation in the bond strength values at any of the test ages. There is nearly 80 % increase in the slant shear bond strength value at the end of 7 days when compared with the values for the same temperature condition at the end of 1 day.

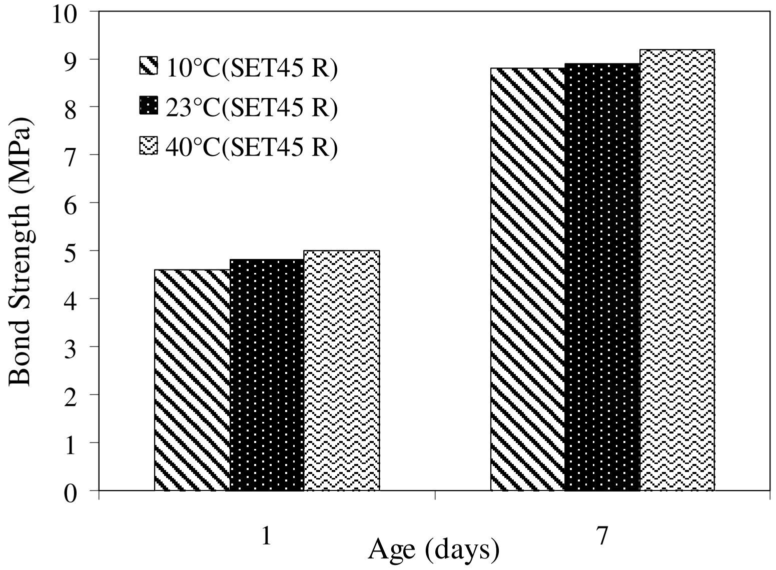


Figure 4.10 Bond strength values for SET 45®mixtures cast with materials at different temperatures

4.3 ThoRoc® 10-60

In this section the results of the testing carried out for ThoRoc® 10-60 as per the methodology outline for Step 1 and Step 2 for Phase I are summarized. ThoRoc® 10-60 is supplied by the manufacturer pre-mixed with siliceous aggregate.

4.3.1 Step 1 – Mixture Proportioning (Estimation of Aggregate Extension and Water Content for ThoRoc® 10-60)

As supplied ThoRoc® 10-60 mortar was extended by adding 50, 60 and 80 percent of (by weight of the original dry materials) of pea gravel. It was observed that mixture containing 50 percent of pea gravel required 0.4 L of additional water per bag of mortar to obtain a flowable mix. Also, when the mix was cast in the plexi-glass box, a few voids were observed underneath the dowel bar. Similarly, for the mixture containing

60 percent pea gravel, additional 0.4 L of water per bag of mortar was also required to obtain a flowable mix. When that amount of water was added, the mixture appeared to be very cohesive and flowable when it was poured in the plexi-glass box. Upon removing from the plexi-glass box the specimen did not show any voids underneath the dowel. ThoRoc® 10-60 when mixed with 80 % aggregate extension required 0.5 L of extra water per bag of mortar to obtain a flowable mix.

Figure 4.11 shows the average compressive strength at various ages for ThoRoc® 10-60 mixtures with different pea gravel content.

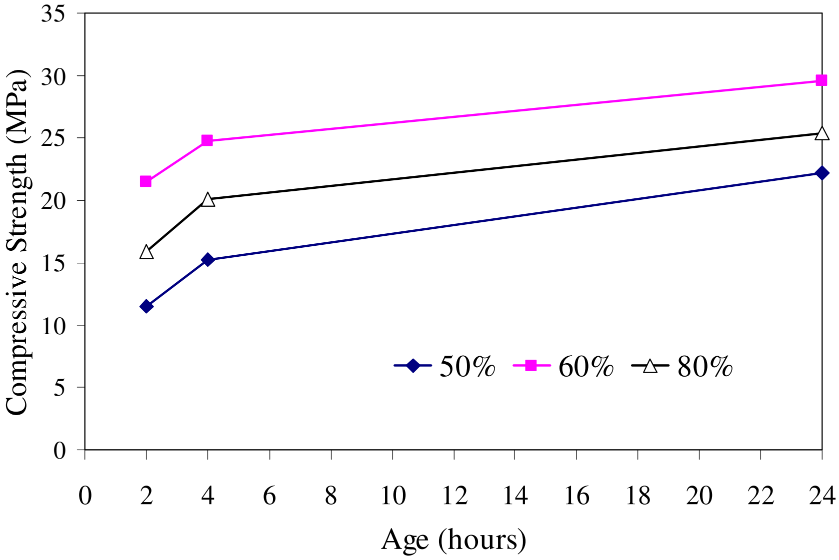


Figure 4.11 Development of compressive strength with different pea gravel extension using ThoRoc® 10-60

The average compressive strength of the mixture containing 50 percent pea gravel was lowest at all ages. Always, the compressive strength of ThoRoc® 10-60 mixture with 80 % pea gravel extension was higher than that with 50 % extension but it was lower than the compressive strength observed for 60% extension. In view of better flowability obtained with 60 % aggregate extension and highest compressive strength that material developed at all ages, it was decided to adopt 60 % aggregate extension for preparation and testing of remaining specimens.

4.3.2 Step 2: Evaluation of the effect of initial material temperature for ThoRoc® 10-60

The ingredients for the mixtures prepared in this section were stored at different temperature conditions (10, 23 and 40°C) as discussed in the section 3.4.1.2. Table 4.3 shows the workability parameter of the mixtures prepared with materials at various temperatures. The mixture prepared with materials at 40°C was relatively stiff and did not flow even after the addition of 0.47 L of extra mixing water. The slump of the mix was 177 mm as shown in Table 4.3. The mixtures cast with materials at 23 and 10°C were flowable and had slump flow values of 482 and 419 mm respectively. Figure 4.13 shows the appearance of the flowable mix and the slump at 10°C.

Table 4.3 Workability parameters of ThoRoc® 10-60 mixtures cast with materials at different temperatures

MATERIAL TEMPERATURE (°C)	**WORKABILITY PARAMETER (MM)**	**EXTRA WATER ADDED (L)**
10	419 (SPREAD)	0.4
23	482 (SPREAD)	0.4
40	177 (SLUMP)	0.47

Figure 4.12 Appearance of ThoRoc® 10-60 mixture prepared with materials at 40°C

Figure 4.13 Appearance of the ThoRoc® 10-60 mixture prepared with materials at 10°C

Table 4.4 Setting time ThoRoc® 10-60 mixtures cast with materials at different temperatures

MATERIAL TEMPERATURE (°C)	**SETTING TIME**	
	INITIAL SETTING TIME (MINUTES)	**FINAL SETTING TIME (MINUTES)**
40	11	27
23	19	32
10	22	37

Table 4.4 gives the setting time for the mortar prepared with materials at different initial temperature conditions. As expected, the final setting time (FST) for mortar produced from materials at 10°C is the highest (37 minutes) and is the lowest (27 minutes) for materials at pre-conditioned at 40°C.

The compressive strength of ThoRoc® 10-60 mixtures as a function of initial material temperature and age is shown in Figure 4.14.

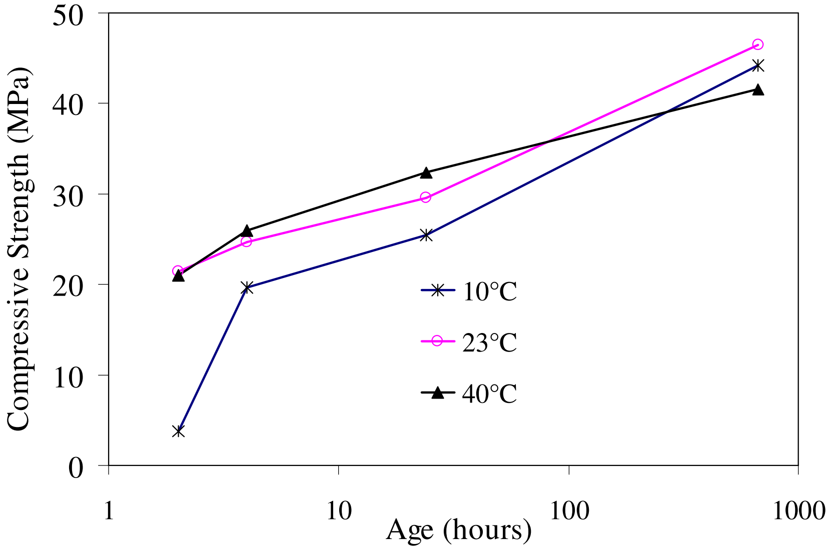


Figure 4.14 Compressive strength of ThoRoc®10-60 mixtures cast with materials at different temperature

The compressive strength at 2 hours for mixture prepared with materials at 10°C is the lowest (4 MPa), whereas for the same age the strength for mixtures prepared with materials at 23 and 40°C is high (21 MPa). The compressive strength curve of mixture prepared with materials at 40°C exhibits less strength gain between 24 hours and 672 hours (28 days) (from 31 MPa to 42 MPa) as compared with mixtures prepared with materials at 10 and 23°C, which exhibit a strength gain of 15 and 17 MPa, respectively. The early rise in strength for mixture with materials at 40°C can attributed to the high temperature of the materials whereas the lowest at 672 hours amongst the three temperature conditions can be attributed to the higher extra water added to the mixture while mixing (Refer to Table 4.3).

Figures 4.15 and Figure 4.16 show, respectively, the drying shrinkage and weight loss of samples for a period of 28 days.

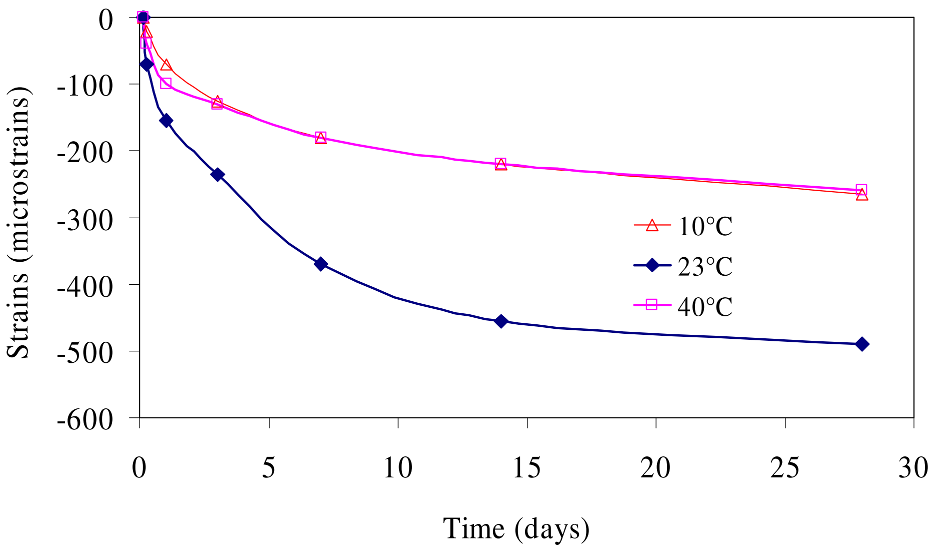


Figure 4.15 Drying shrinkage for ThoRoc® 10-60 mixtures cast with materials at different temperatures

The drying shrinkage is low (200 μm) for specimens stored at 10 and 40°C. The 23°C samples have a high shrinkage of about 500 μm and weight change value of 1.8 %. The low shrinkage values for 40°C can be attributed to the presence of alumina cement (30%) in the formulation of ThoRoc®10-60 (based on manufacturer's data provided in Appendix D). In materials containing alumina cement, the higher temperature during curing leads to formation of stable hydrates which in turn, results in lower shrinkage (Hewlette, 1988).

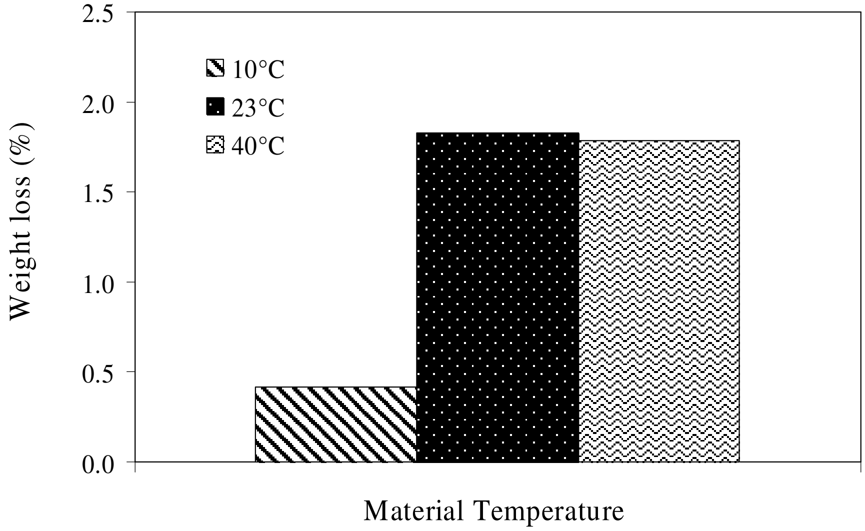


Figure 4.16 The 28-day weight change for ThoRoc® 10-60 mixtures cast and cured with materials at different temperatures

The weight loss of speciemns over at end of 28 days is shown in Figure 4.16. The weight loss for drying shrinkage specimens stored at 10°C was the least (about 0.8%). The weight loss for specimens prepared and stored with materials at 23 and 40°C is equal(1.8%).

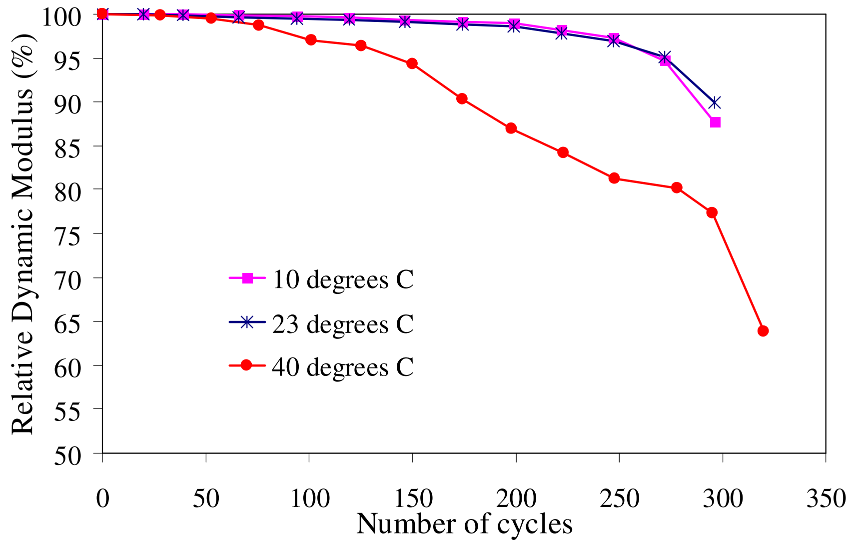


Figure 4.17 Loss of relative dynamic modulus of elasticity over 300 cycles of freezing and thawing for ThoRoc® 10-60 mixtures cast with materials at different temperatures

Figures 4.17 and Figure 4.18 show the change in relative dynamic modulus and the weight loss over 300 cycles of freezing and thawing for specimens prepared with materials at different temperatures. The mixtures prepared with materials at 23 and 10°C did exhibit only moderate (about 10%) loss in modulus at the end of 300 cycles. The loss in weight was also moderate until 200 cycles after which the samples exhibited a sudden drop in weight (see Figure 4.18). The resistance to freeze-thaw of samples cast with materials at 40°C was much lower (about 40 percent reduction in modulus at the end of 300 cycles). The loss in weight for these samples is also highest in comparison to the samples cast with materials at 10 and 23°C.

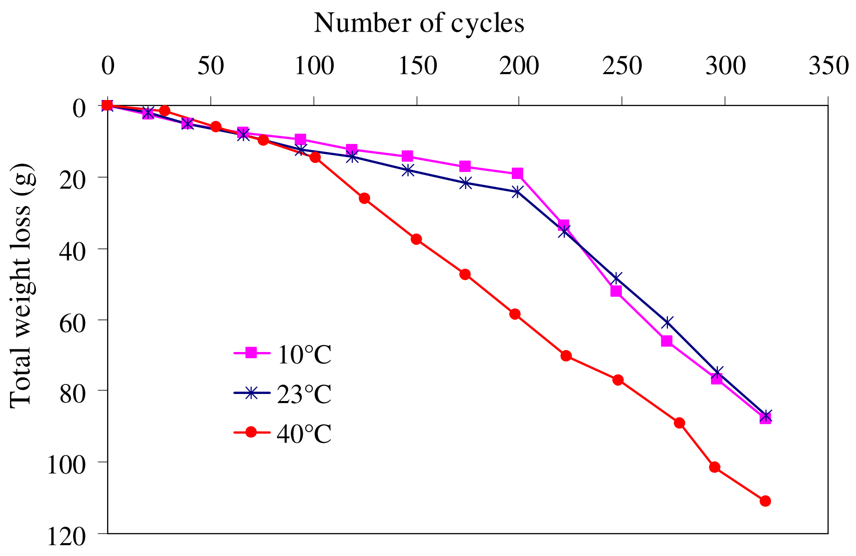


Figure 4.18 Weight loss over 300 cycles of freezing and thawing for ThoRoc® 10-60 mixtures cast with materials at different temperatures

Figure 4.19 shows the surfaces of the specimen at 1 day tested for slant shear bond strength for ThoRoc®10-60 prepared with materials pre-conditioned to 23°C. It can be observed that the failure of the specimen occurred along the plane joining the portland cement based concrete to the repair concrete.

Figure 4.19 Slant shear bond strength test sample for ThoRoc®10-60

Figure 4.20 gives the results of the slant shear bond strength for the different initial material temperatures, measured at 1 and 7 days of casting. In both cases, the initial temperature of the material did not influence the test results. The increase in strength over a period of 7 days is almost 80% for all the specimens prepared with different pre-conditioning temperature.

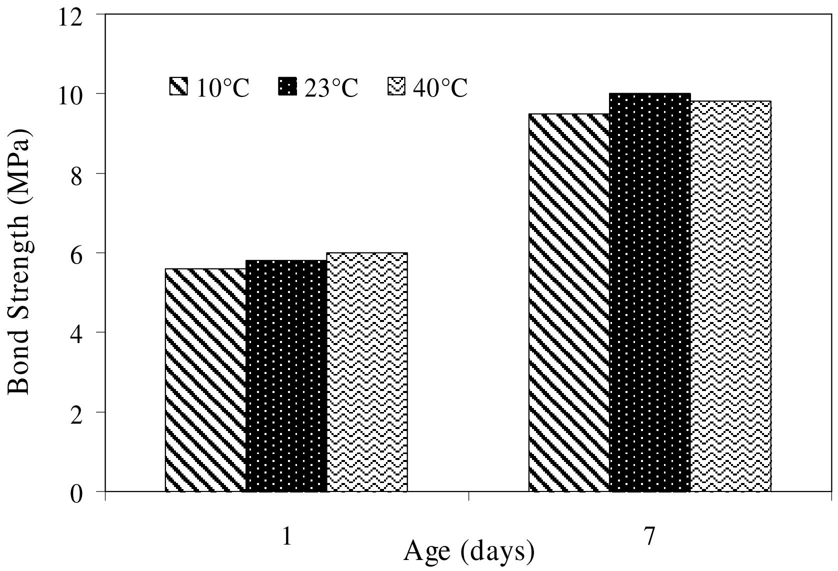


Figure 4.20 Bond strength values for ThoRoc® 10-60 mixtures cast with materials at different temperatures

4.4 Highway Dowel Bar Retrofit Mortar

In this section, the results of testing carried out using HDBR for Step 1 and Step 2 of Phase I are presented. Like ThoRoc® 10-60 this material is also alumina cement based with some amount of portland cement (refer Appendix-D). In Step 1 different aggregate extensions were evaluated to arrive at the optimum content of extension for HDBR mixtures.

4.4.1 Step 1 – Mixture Proportioning (Estimation of Aggregate Extension and Water Content for HDBR)

The manufacturer of Highway Dowel Bar Retrofit Mortar (HDBR) does not specify any limits on extension of aggregates that can be used. After consultations with the manufacturer, three different aggregate contents namely 60, 80 and 100 % of 1 bag of dry material was adopted. The manufacturer allows 0.4 L addition of extra water as required when the repair concrete is extended using pea gravel.

Figure 4.21 shows the compressive strength development for the different percentages of pea gravel added to HDBR. The recommended water per 22.7 kg of repair material is 2.8 L. It was observed that the mixture containing 60% pea gravel required 0.18 L of additional water to obtain good flowability. This mixture also had the highest compressive strength of 29 MPa at 24 h. Mixtures cast with 80 and 100% aggregate extension required 0.22 L and 0.25 L, respectively, per 22.7 kg of dry material. Since the mixture with 60% pea gravel extension showed highest strength and had low water demand for workability, this mixture was adopted for evaluation of other properties.

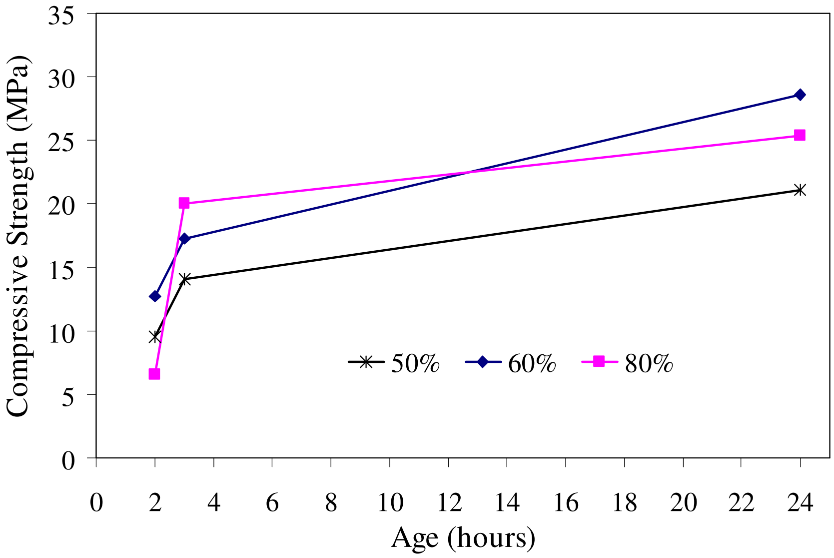


Figure 4.21 Development of compressive strength with different pea gravel content for HDBR concrete

4.4.2 Step 2 Evaluation of the Effect of Initial Material Temperature for HDBR

HDBR repair material was analyzed for fresh and hardened concrete properties by extending the mixture with 60 percent pea gravel based on the observations presented in section 4.2.1. The repair material was evaluated for different temperature conditions i.e. 10, 23 and 40°C.

Table 4.5 gives the slump flow and additional water required to obtain the desired workability parameters. Additional water of 0.18 L was required for mixtures cast at 10 and 23°C whereas 0.24 L of water was required for mixture cast at 40°C. The highest spread (623mm) by the slump test was observed for concretes cast for materials with initial temperature of 23°C. Figure 4.22 shows the appearance of the spread obtained for this mixture.

Table 4.5 Workability parameters of HDBR mixtures cast with materials at different temperatures

MATERIAL TEMPERATURE (°C)	**WORKABILITY PARAMETER (MM)**	**EXTRA WATER ADDED (L)**
10	533	0.18
23	623	0.18
40	533	0.24

Figure 4.22 Appearance of the HDBR concrete with 60% aggregate extension and materials at 23°C

Table 4.6 gives the initial and final setting time obtained for various temperature conditions. The mixtures cast at 10oC required the highest time for final set (40 minutes).

Table 4.6 Setting time of HDBR mixtures cast with materials at different temperatures

MATERIAL TEMPERATURE (°C)	**SETTING TIME**	
	INITIAL SETTING TIME (MINUTES)	**FINAL SETTING TIME (MINUTES)**
40	10	18
23	19	32
10	22	40

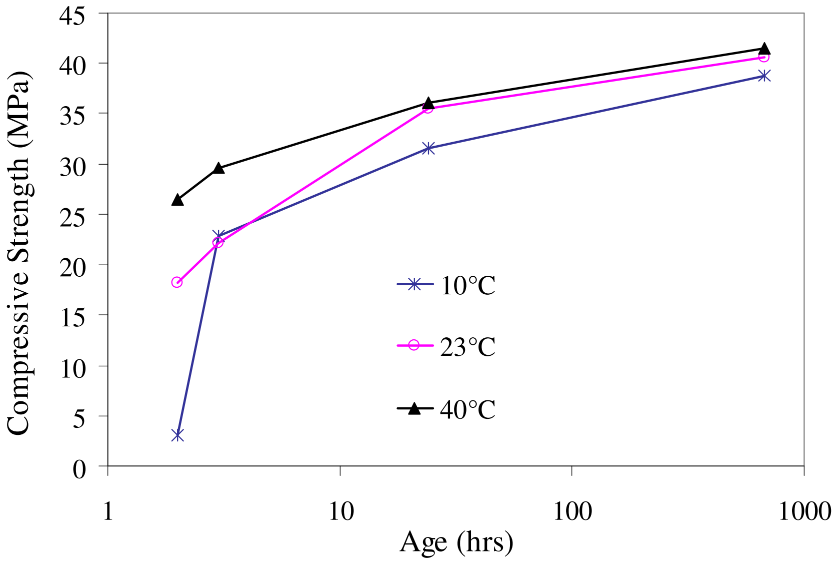


Figure 4.23 Compressive strength at various ages of HDBR mixtures with materials at different temperatures

Figure 4.23 is a graph showing the compressive strength at various ages for mixtures cast at different temperatures. It can be observed that values are scattered at the initial ages whereas they are nearly equal at 672h (28 days). The mixtures cast with materials pre-conditioned at 10°C have lower strength values (4.5 MPa) at 2 h as compared to the other two temperature conditions. Comparing the strength values for mixtures cast at 23 and 40°C, it can be seen that the mixture cast at 23°C has considerably lower strength at 2 and 3 hours, respectively, as compared to the mixture cast at 40oC but the strengths of both mixtures are equal at 24 hours.

Figure 4.24 gives the drying shrinkage values for HDBR mixtures over a period of 28 days. The shrinkage values for mixtures cast 23 and 10°C is nearly equal (590 and 620 µm respectively), whereas the shrinkage of mixture cast with materials at 40°C and stored at the same temperature is comparatively lower at 490 µm. If we compare the percentage weight loss for the same samples it can be seen from Figure 4.25 that the values are nearly equal for mixtures cast 40 and 10°C (1.78 % and 1.8% respectively). The percentage weight loss for mixture cast with materials at 23oC is lowest at 1.25%.

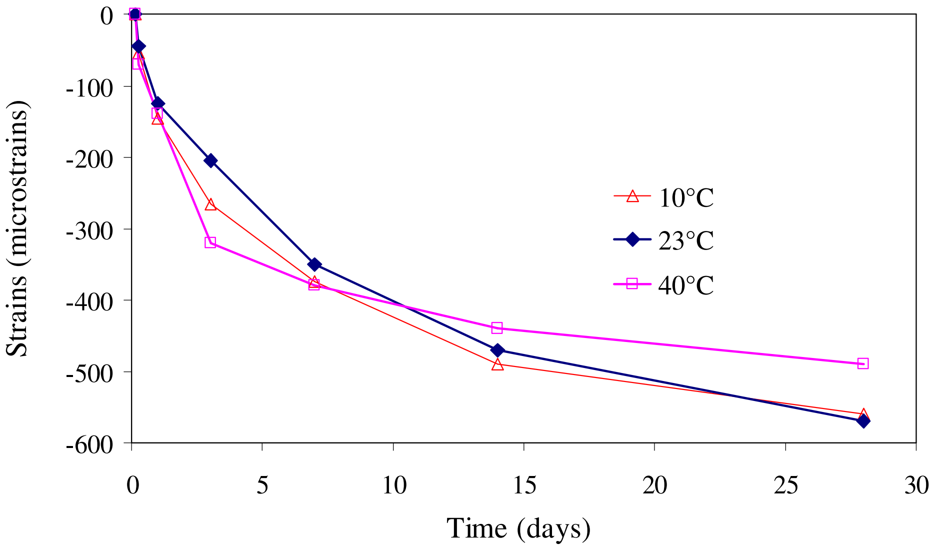


Figure 4.24 Drying shrinkage values of HDBR mixtures cast with materials at different temperatures

The low shrinkage values for mixture stored at 40°C can be related to the presence of alumina cement in the formulation of HDBR (refer Appendix D for details). Continuous curing at 40°C results in formation of stable hydrated product in concretes with high amount of alumina cement making them less susceptible to shrinkage.

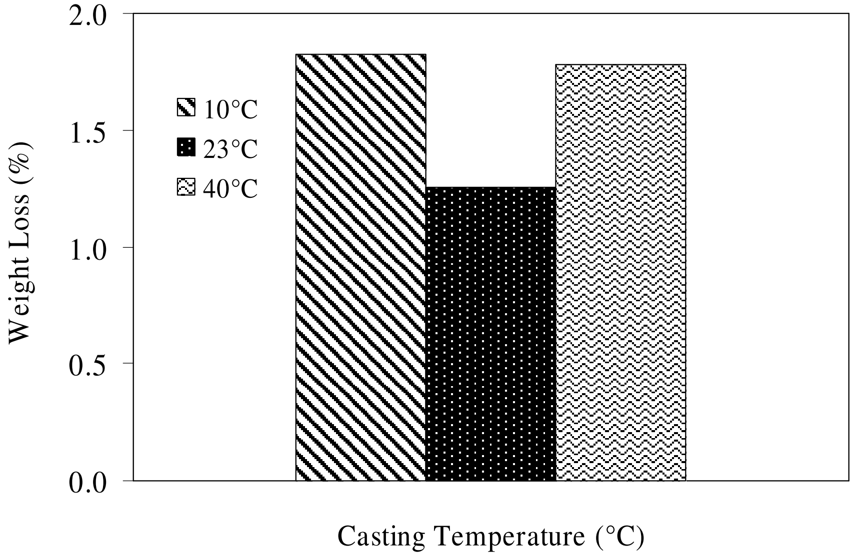


Figure 4.25 The 28-day weight change for HDBR mixtures cast with materials at different temperatures

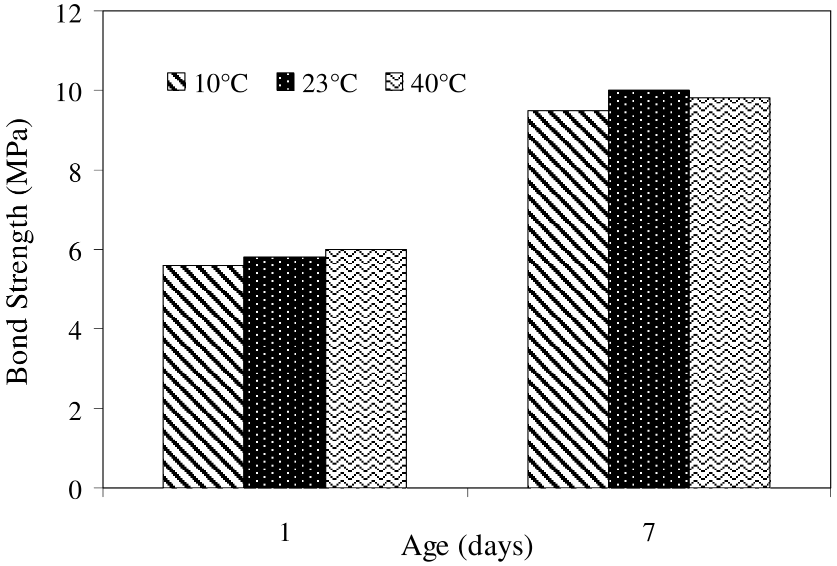


Figure 4.26 Bond strength values for HDBR mixtures cast with materials at different temperatures

The bond strength values for all the temperature conditions at 1 day and 7 day are nearly equal to each other as can be seen in Figure 4.26. At 1 day the bond strength value is ranging from 5.5 to 6 MPa whereas at 7 days it varies from 9.5 to 10 MPa.

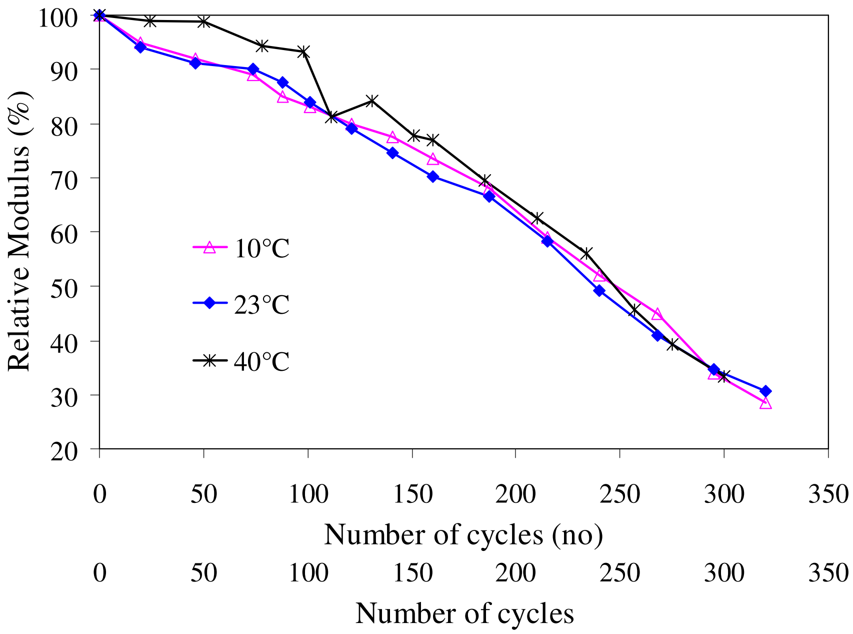


Figure 4.27 Loss of relative dynamic modulus of elasticity over 300 cycles of freezing and thawing of HDBR mixtures cast with materials at different temperatures

Figure 4.27 and Figure 4.28 show the loss in relative dynamic modulus and weight loss for 300 cycles of freezing and thawing of mixtures cast with materials at various temperatures. The relative modulus is 30 and 35 % at 300 cycles for mixtures cast at 23 and 40°C respectively. It can be seen that the HDBR samples exhibited some increase in weight as the freezing and thawing cycles were increased but overall the specimens lost weight at the end of 300 cycles. All the specimens did loose some amount of paste due to scaling as can been seen in Figure 4.29. The specimens prepared with materials pre-conditioned at 10°C exhibit a lower loss of weight but the loss in dynamic modulus is nearly same as that for the other two conditions.

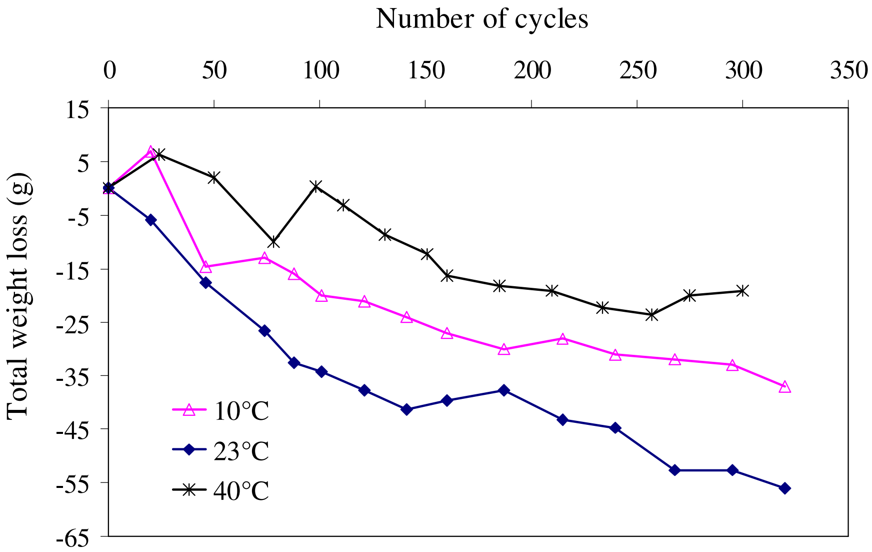


Figure 4.28 Weight loss over 300 cycles of freezing and thawing of HDBR mixtures cast with materials at different temperatures

Figure 4.29 Appearance of HDBR mixture subjected to 300 cycles of freezing and thawing

4.5 Five Star Highway Patch Cement

The Five Star Patch cement was not analyzed for pea gravel extension since this product is not available as a pre-mixed bag product. The final proportion of the concrete mixture with the FSHPC was developed using trial and error process and was given in Chapter 3 (Table 3.5).

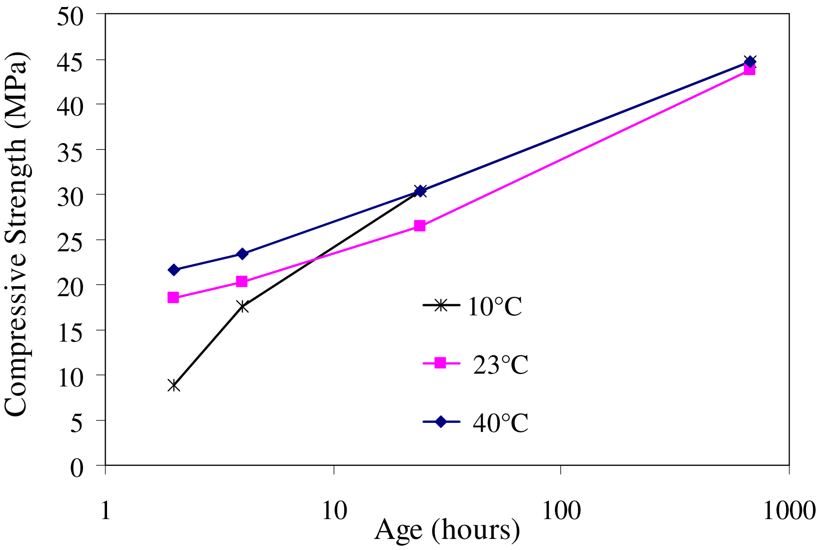


Figure 4.30 Compressive strength of FSHPC mixtures cast with materials at different temperatures

Figure 4.30 shows the compressive strength achieved at 2, 4, 24 and 672 h (28 days) for FSHPC mixtures cast with materials at different temperatures. The strength of the mixture cast at 40°C is 21.5 MPa at 2 h and increases progressively, whereas the compressive strength of the mixture cast at 10°C is low (9 MPa) at 2 h but increases sharply after that and it is equal to the compressive strength of the mixture cast with materials at 40°C at 24 h.

Figure 4.31 shows the setting time values for FSHPC mixtures cast with materials at different temperatures. For mixture cast with materials at 10°C the initial setting time (IST) and the final setting time were highest at 22 and 40 minutes respectively. The setting time was lowest for mixture with materials at 40°C (12 and 21 minutes for IST and FST).

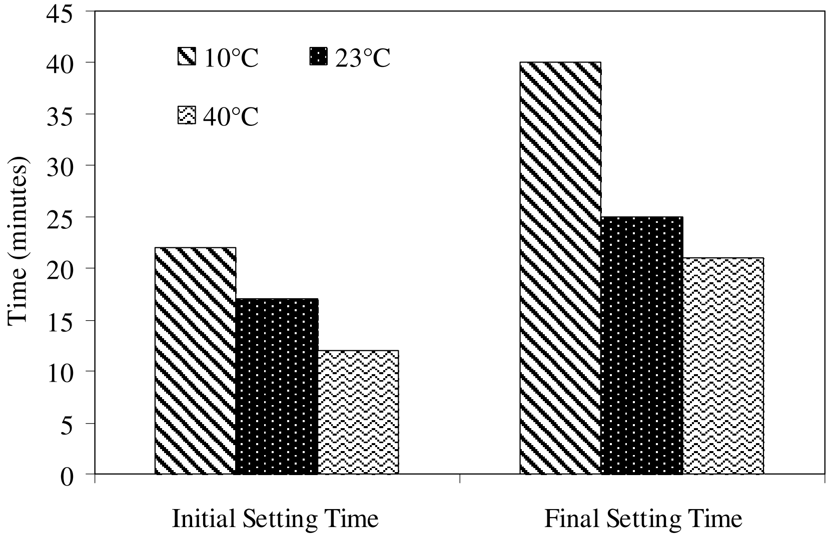


Figure 4.31 Plot of setting time of FSHPC mixtures cast with materials at different temperatures

Figure 4.32 is a plot of drying shrinkage for different temperature conditions for FSHPC. For the initial 3 days after casting the samples for all the temperature conditions have almost similar drying shrinkage of about 125μm. After, three days the change in length increases rapidly for samples cast with materials at 23°C and is 315 μm at the end of 28 days.

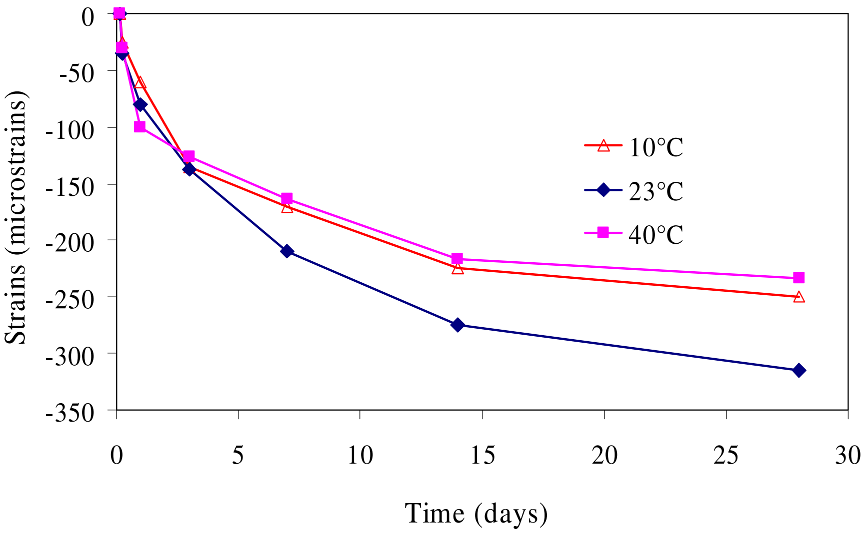


Figure 4.32 Drying shrinkage for FSHPC mixtures cast with materials at different temperatures

In Figure 4.33 the rate of weight change at the end of 28 days is shown. The samples cast with materials at 40°C show greatest loss in weight in comparison to the other temperature conditions. The complete composition of FSHPC is not provided by the manufacturer except that it is based on hydraulic cement. Hence, a clear evaluation of low strains at 40°C could not be provided.

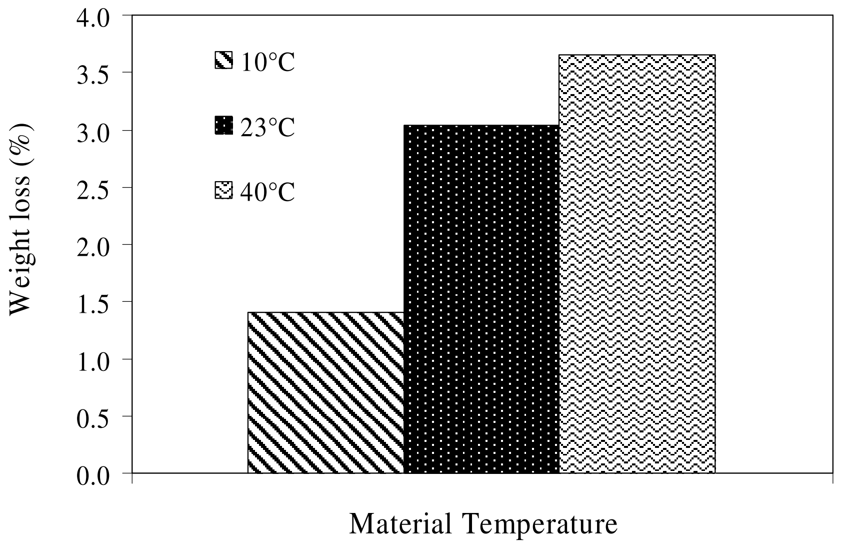


Figure 4.33 The 28-day weight change for FSHPC mixtures cast with materials at different temperatures

Figure 4.34 shows the development of bond strength over 7 days for FSHPC. The bond strength of FSHPC cast with materials pre-conditioned at different temperature conditions is close to the requirement of 6.8 MPa at 1 day and 10.4 MPa at 7 days.

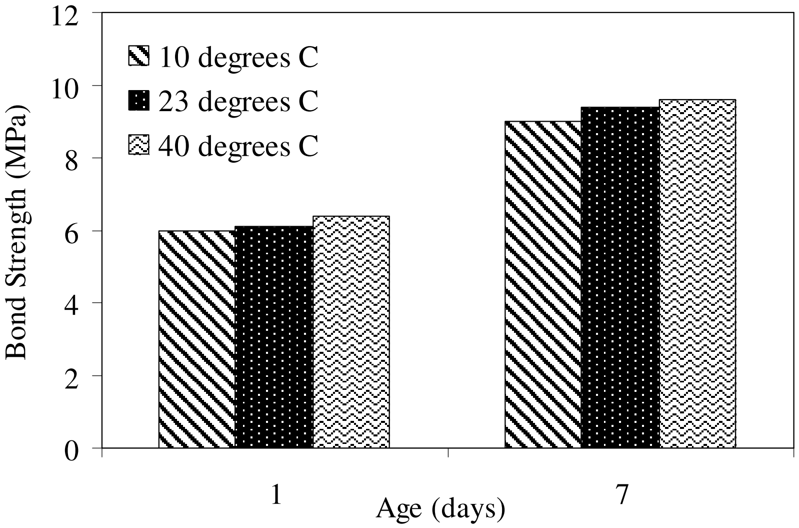


Figure 4.34 Bond strength values for FSHPC mixtures cast with materials at different temperatures

The freeze-thaw resistance of FSHPC was low. When specimens of FSHPC prepared with materials at different temperatures were subjected to alternate freezing and thawing, they failed within about 20 cycles. Figure 4.35 shows a specimen having numerous deep cracks resulting from the freeze-thaw damage. It has to be noted that the mixtures with FSHPC were prepared as per the manufacturer's recommendation and no changes in the mixture design was made. Also, as per the manufacturer's data sheet this material has 90 % durability factor (refer to Appendix-D). It should also be noted, however, that, compared with all the other materials FSHPC had no entrained air (see Table 4.6) and so the low freeze-thaw resistance is not unexpected.

Figure 4.35 Failure of FSHPC mixture within 20 cycles of freezing and thawing

4.6 Comparison of Repair Materials

This section compares the fresh and hardened concrete properties of all the commercial repair materials.

Figure 4.36 shows a graph comparing the slump flow of all the repair materials at different temperatures. For materials pre-conditioned at 40°C, ThoRoc™10-60 has the lowest workability parameter (slump of 177 mm) whereas HDBR and FSHPC had the highest spread at 620 mm. ThoRoc™10-60 and SET®45 have comparable spread at 23 and 10°C and is lower than HDBR and FSHPC. FSHPC has the highest slump flow for all temperature conditions amongst all the repair materials studied. From Figure 4.36 it can be concluded that temperature of the materials has a stronger impact on ThoRoc™10-60 the most whereas Set 45® and FSHPC do not show much change.

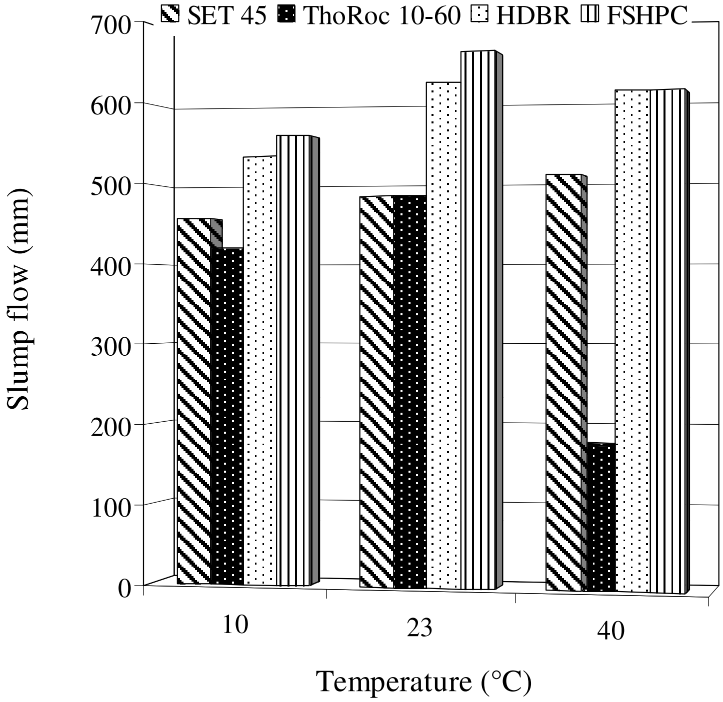


Figure 4.36 Comparison of slump at different casting temperatures

As mentioned in earlier sections an extra amount of water was added to achieve flowability for all materials except FSHPC. Figure 4.37 is a plot showing the ratio of extra water added to the recommended water content as per the manufacturer. Amount of water added in addition to that recommended by the manufacturer was highest for ThoRoc™ 10-60 for all temperature conditions. Due to high water cement ratio FSHPC did not require additional water for flowability at different temperature conditions.

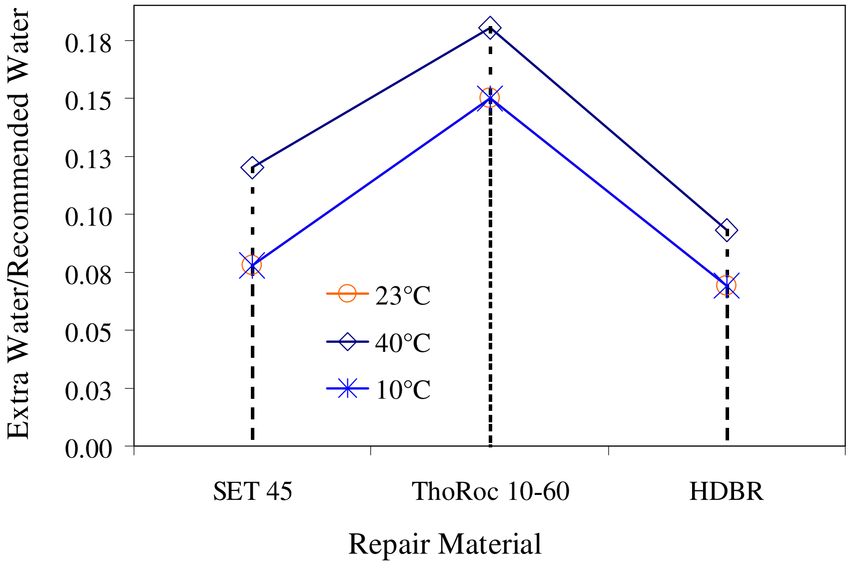
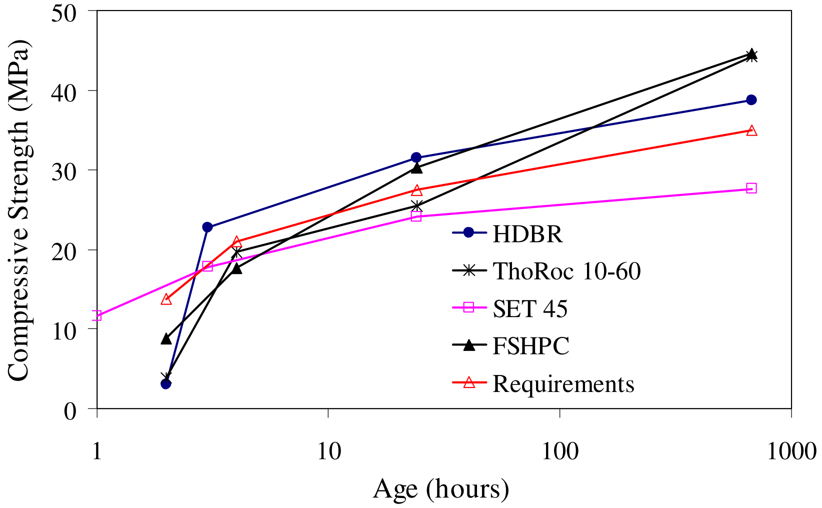


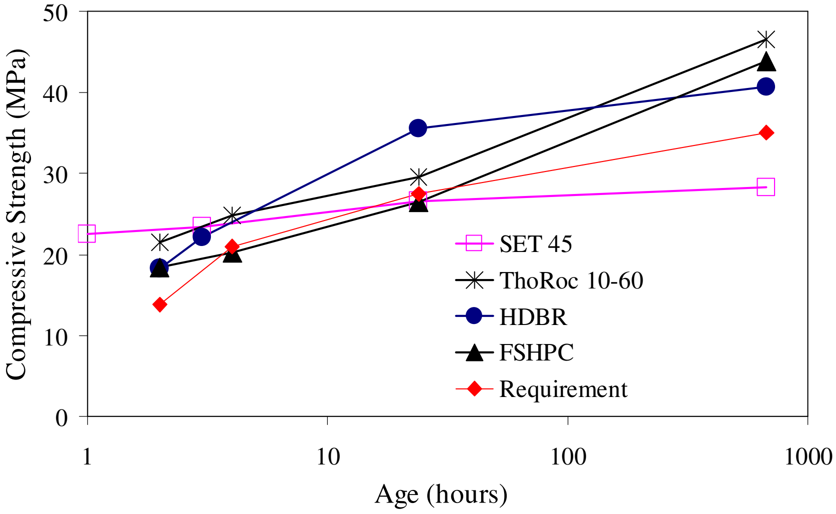
Figure 4.37 Changes in water to cementitious ratio

The development of compressive strength of all the commercial repair materials is compared through plots in Figure 4.38 a, b and c. It can be observed that all the commercial repair materials except SET 45® R do not achieve the required strength at 1 hour (see Table 3.13 of Chapter 3). However, required strength of 27.5 MPa at the end of 24 h is not achieved by of SET 45® R and HW.



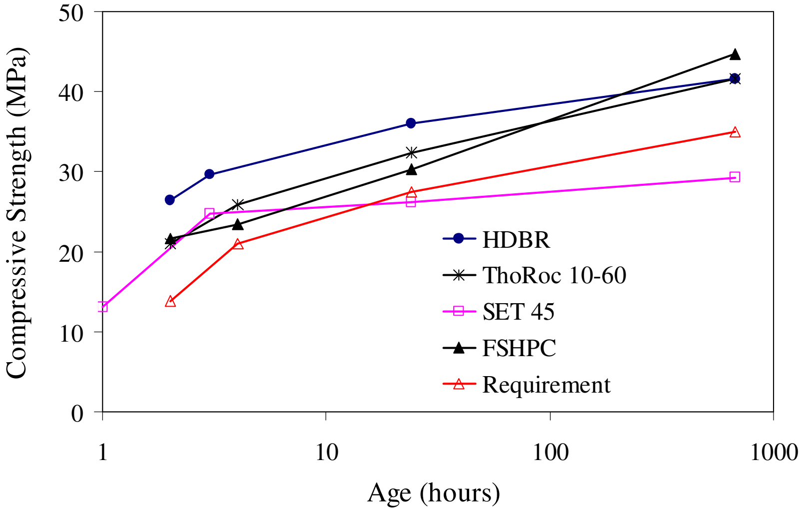
(A)

Figure 4.38A Comparison of Development of Compressive Strength at Various Ages FOR (A)



(B)

Figure 4.38b Comparison of development of compressive strength at various ages for (b) 23°C



(c)

Figure 4.38c Comparison of development of compressive strength at various ages for (c) 40°C.

At 24 h only HDBR and ThoRoc™10-60 meet (35 MPa and 29.5 MPa, respectively) the strength requirements for materials at 23°C of 27.5 MPa. Strength developments of FSHPC consistently falls below the requirements untill 24 h but it meets the requirement of 35 MPa at the end of 28 days. All commercial repair materials cast at 40°C exhibit strength development above the requirements of those set for 23°C except SET 45 at the end of 28 days. At lower temperature of 10°C none of the materials achieve appreciable strength except for SET 45 at the end of 1 h or 2 h. But, at the end of 4 h all the three non-performing materials gain strength and perform better than SET 45 at the end of 28 days. The inability to gain strength at the end of 1 h or 2 h can be related to the setting times of these materials.

Figure 4.39 shows the setting time of all the commercial materials pre-conditioned to different temperatures prior to carrying out the test. The low rate of strength gain for materials at 10°C can be attributed to the high final setting time for all the materials. SET®45 R has comparable setting time at 10 and 23°C. HDBR has the highest setting time amongst all materials at 10 and 23°C.

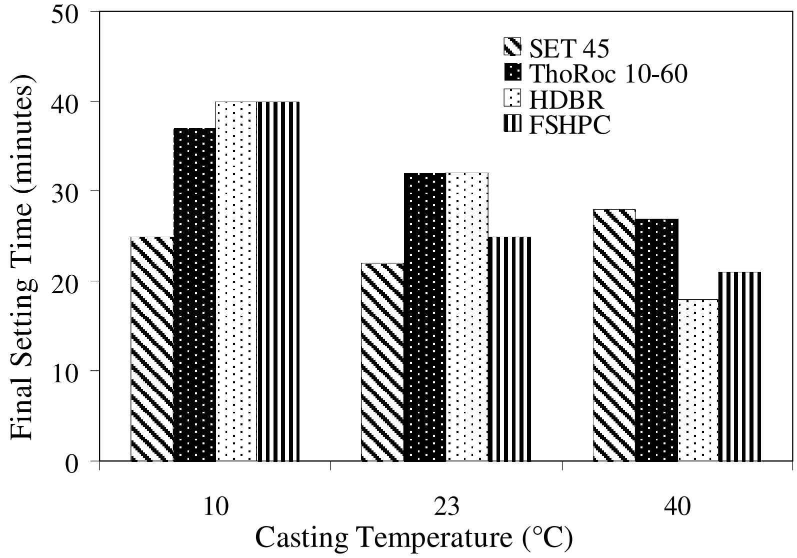
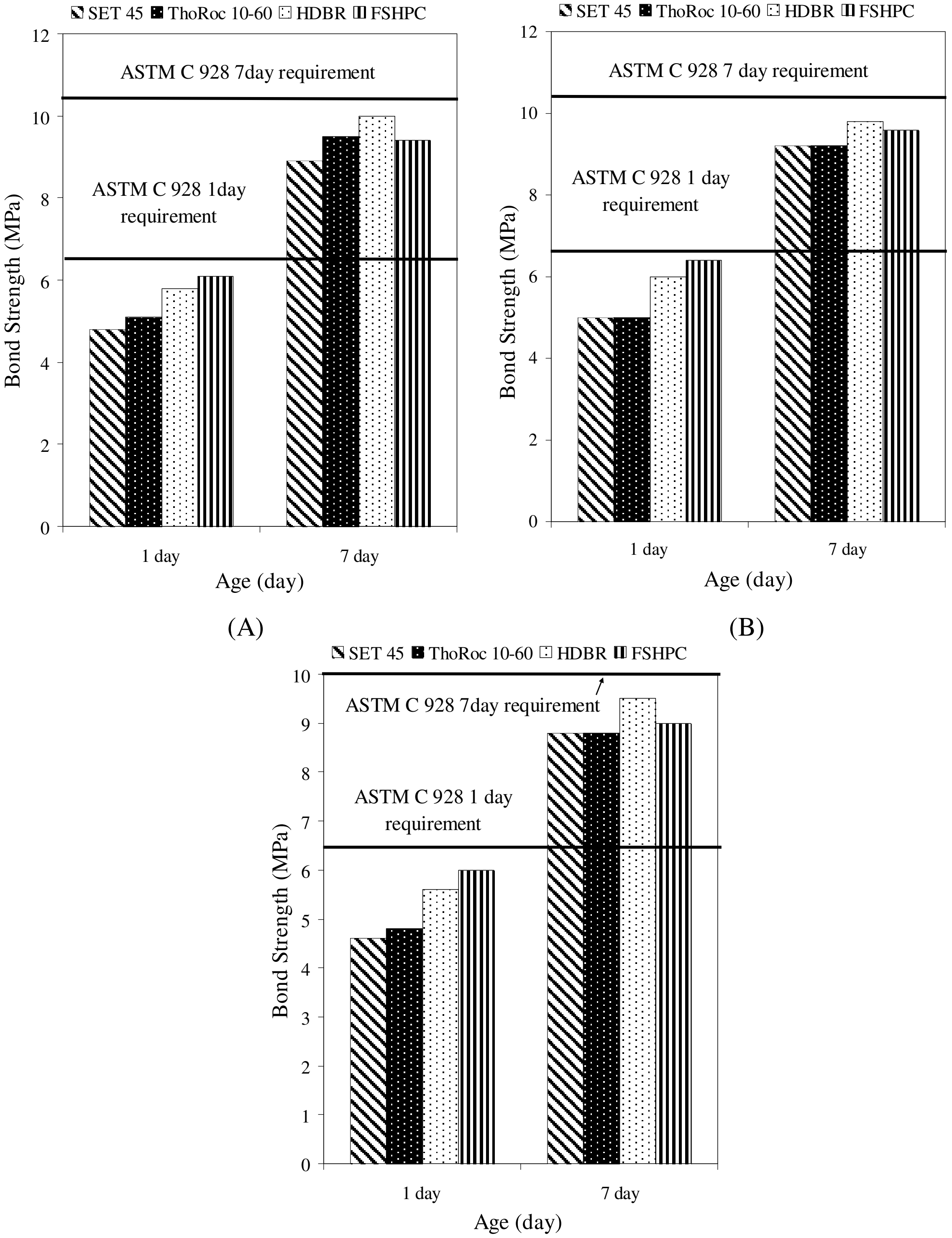


Figure 4.39 Setting time of commercial repair materials

For materials at 40°C, SET®45 HW has the highest setting time (28 minutes) amongst all materials. This can be attributed to the different formulation of SET®45 used for 40°C (SET®45 HW).

Figure 4.40 shows a comparison of development of slant shear bond strength for all the repair materials at 23, 40 and 10°C. All the materials perform poorly and do not meet the requirement of ASTM C 928 for 23°C. At the end of 1 day, FSHPC consistently has the highest slant shear bond strength for all the temperature conditions, whereas the end of 7 days HDBR exhibits the highest bond strength for all temperature conditions.



(A) (B)

(c)

Figure 4.40 Comparison of slant shear bond strength (a) 23°C (b) 40°C and (c) 10°C

The freeze durability of all the commercial repair materials for different pre-conditioned temperatures is compared in Figure 4.41. ThoRoc™10-60 has the highest resistance to freezing and thawing and has a relative modulus of more than 60% for all the three temperature conditions at the end of 300 cycles. Amongst HDBR and SET®45, HDBR performs poorly for all the temperature conditions at the end of 100 and 200 cycles. At the end of 300 cycles the relative modulus of SET®45 and HDBR is comparable (about 35%). To understand the large loss of relative dynamic modulus the hardened air content of the commercial repair materials at 23°C was determined.

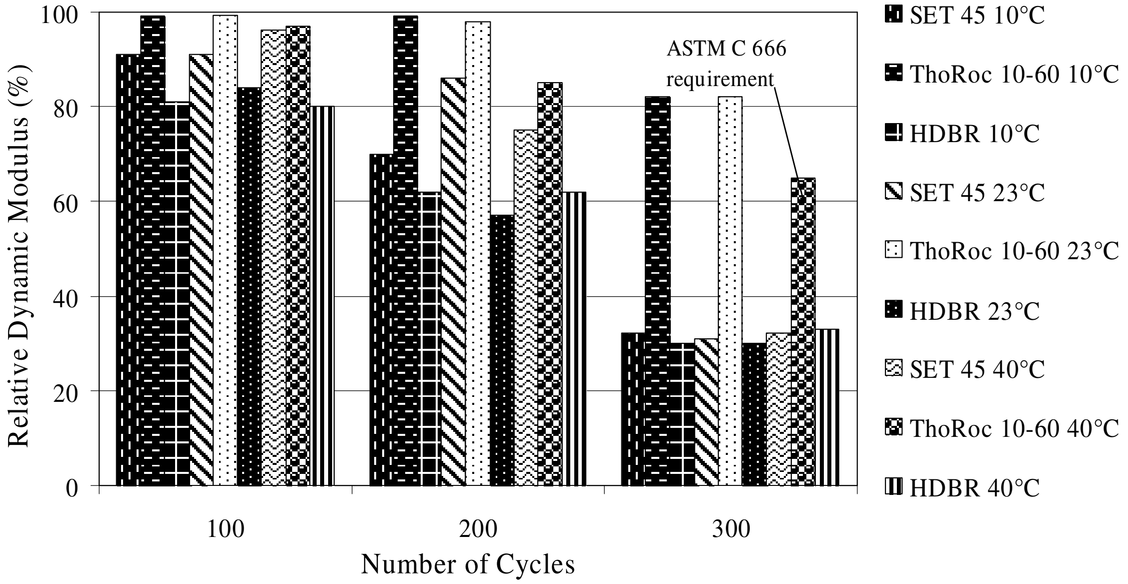


Figure 4.41 Comparison of loss of relative dynamic modulus of elasticity over 300 cycles for CRSMs pre-conditioned at different temperatures

Table 4.7 gives details of the hardened air content for all the materials. ThoRoc™10-60 has the highest air-content of 6.2 % with a spacing factor of 545 µm. The lowest air-content was observed for FSHPC with highest spacing factor of 2732 µm.

There is strong experimental evidence that the spacing of the voids is the key factor governing the frost resistance of concrete. For ordinary concretes, it is generally accepted that the spacing factor should not exceed 200 or 250 µm. The actual chemical composition of the CSRMs used in this study could not be determined except for the basic information provided in Chapter 3. Hence, the accepted spacing factor for normal concretes cannot be truly applied for repair concrete. The low loss of modulus of ThoRoc™10-60 could be attributed to the high air content though its spacing factor is not within the accepted limits for normal concretes.

Table 4.7 Air content and spacing factor for CRSM cast with material at 23°C

MATERIAL	**AIR CONTENT (%)**	**SPACING FACTOR (MM)**
SET 45	4.8	561
THOROC 10-60	6.2	545
HDBR	3.7	1020
FSHPC	1.6	2732

SET 45® is a phosphate cement based repair material which is typically prepared with magnesium phosphate (MgO), mono ammonium phosphate (NH4H2PO3), borax and fly ash. Information regarding presence of any air entraining agent was not provided by the manufacturer but it has been reported elsewhere by researchers that many air-bubbles are generated during the casting of phosphate based cements due to the release of NH3 and H2 but the size of the bubbles is not provided (Yang et al., 2002). During the point count test of SET 45 a large amount of entrapped voids were observed (2.5%). This observation is made based on the comparison with nominal size of about 0.05 mm to 1.25 mm entrained air bubbles of normal concrete.

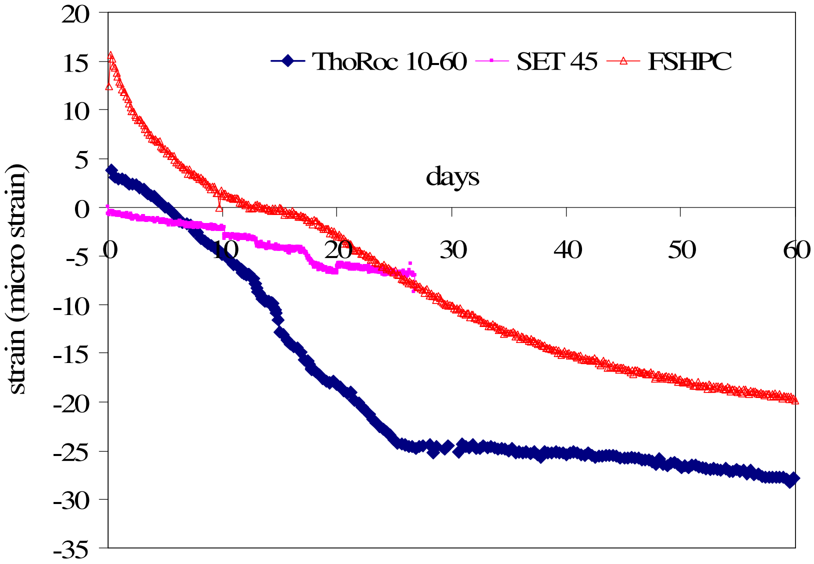
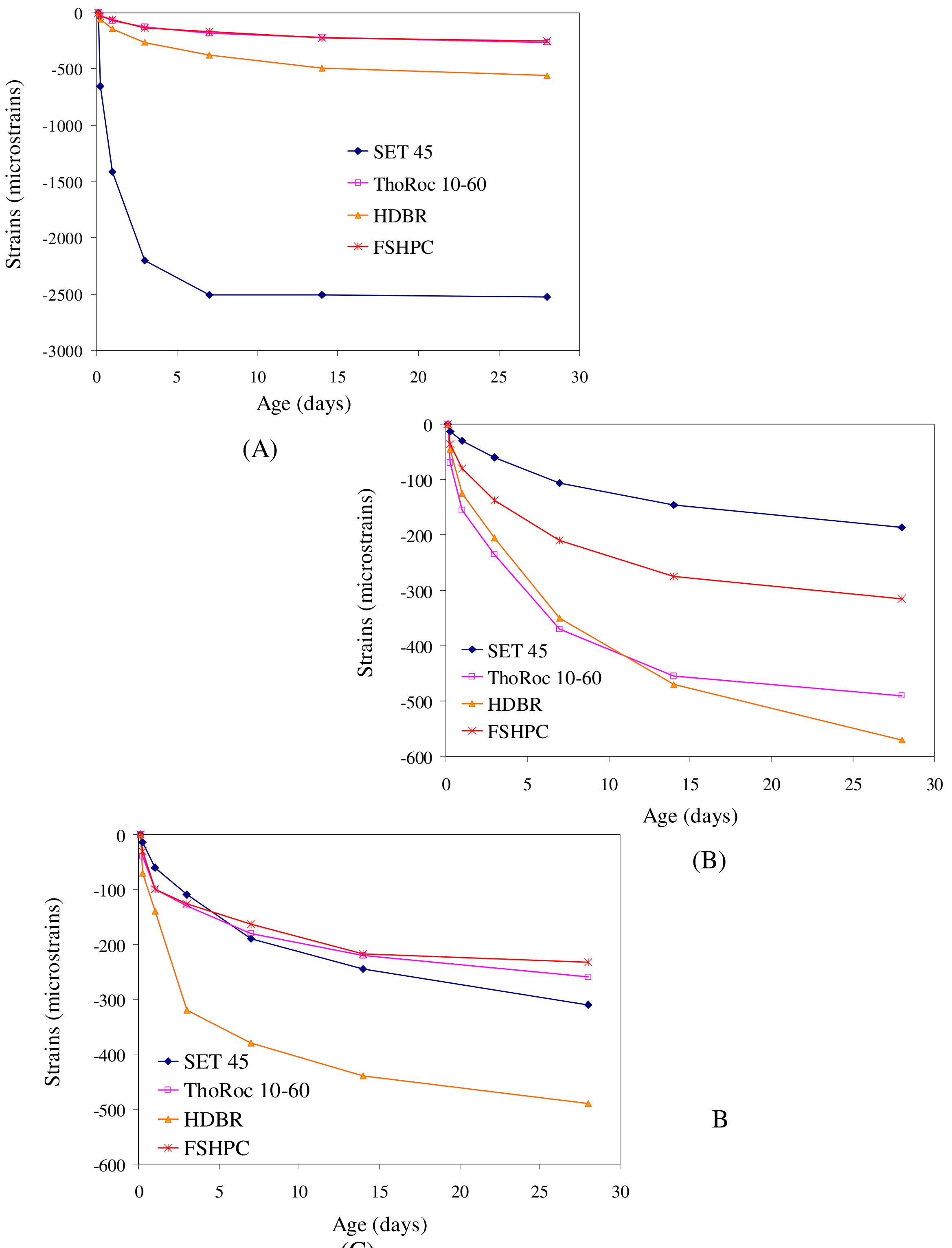


Figure 4.42 Strains developed during restrained ring shrinkage test

Figure 4.42 shows the strain developed for the restrained ring test for ThoRoc™ 10-60, SET 45®R and FSHPC. All rings were prepared using materials at 23°C. None of the rings developed cracks within the time frame shown in the graph. The test was discontinued for SET 45 after 28 days due to paucity of time. The highest shrinkage strains developed for ThoRoc™10-60. As per ASTM C 1581, the potential for cracking is low if the net time to cracking is higher than 28 days.

In Figure 4.43a comparison of the drying shrinkage over a period of 28 days, of all the commercial rapid setting materials at different storage temperatures is shown. For samples stored at 10°C, ThoRoc™10-60 and FSHPC had comparable shrinkage throughout the entire test period. HDBR has shrinkage of about 500 µm. SET 45®R had the highest amount of shrinkage at the end of 28 days (more than 2500 µm). High shrinkage values for SET 45®R can be attributed to the formulation of the material as explained in section 4.2. Lower shrinkage values for all the other materials can be attributed to the presence of high humidity (90 % RH).

For samples stored at 23°C the lowest strains were observed in SET 45®R (190 µm) and the highest were observed for HDBR (590 µm) (refer to Figure 4.43b). For mixtures stored at 40°C the shrinkage values are plotted in Figure 4.43c. Except for SET 45®HW, all the other CSRMs used in this phase show lower shrinkage strains for this temperature condition in comparison to the other two temperature conditions evaluated earlier. As explained in section 4.3, presence of alumina cement in the formulation of these cements and curing of these concretes at higher temperature reduces the shrinkage values.



(A)

(B)

B

(C)

Figure 4.43 Comparison of drying shrinkage for different CSRMs at (a) 10° C, (b) 23°C and (c) 40°C

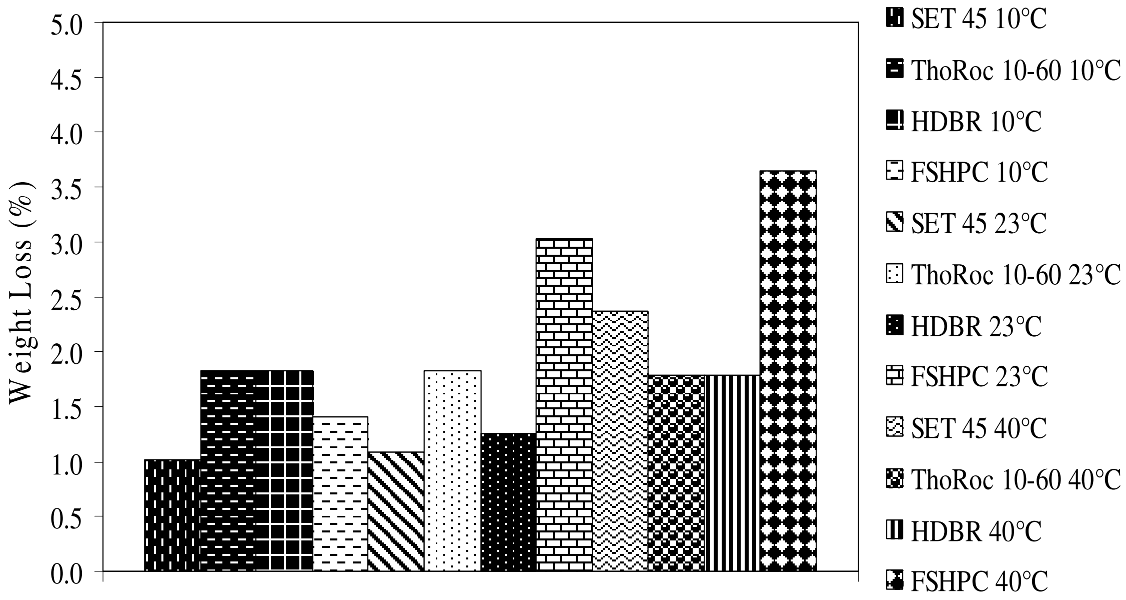


Figure 4.44 Comparison of Weight Loss for Different CRSMs

Figure 4.44 shows the weight loss after 28 days for the drying shrinkage samples stored at varying temperature and RH conditions. All the commercial rapid-setting cements had the lowest weight loss for samples stored at 10°C and 90 % RH. At this test condition, THoRoc®10-60 and HDBR have the highest weight loss followed by FSHPC and SET 45®R respectively. For samples stored at 23°C and 40°C and 50 % RH, FSHPC had the highest weight loss.

CHAPTER 5: DEVELOPMENT OF RAPID-SETTING SELF-CONSOLIDATING CONCRETE (PHASE –II, STEP 1)

5.1 Introduction

Self-consolidating concrete (SCC) can be considered to be a suspension of solid materials such as cement, supplementary cementitious materials and aggregates of different sizes in water and various admixtures. SCC mixtures need to be designed for a combination of filling ability, passing ability through and around reinforcement and resistance to segregation. Different design methods have been developed for development of a stable and flowable SCC. The method for achieving self-compactability involves mainly high deformability of the paste or mortar and resistance to segregation between coarse aggregate and mortar when the concrete flows through the confined zone of reinforcing bars. The frequency of collision and contact between two aggregate particles can increase as the relative distance between them reduces resulting in increased internal stress. In such a case, the energy required for flowing can be consumed by the increased internal stresses resulting in blockage of aggregate particles. By limiting the amount of aggregate content increase in internal stresses can be avoided. Similarly, a low viscous paste is required for a stable SCC since it helps in reducing the internal stresses which could hinder the flowability (Okamura et al., 2000). To achieve high deformability, reduction of water/cementitious ratio and usage of superplasticizer is a must for production of SCC. According to Khayat et al., (Khayat & Daczko, 2002) the guiding principles for development of SCC are to maintain a proper control of total water content and HRWR dosage, and to maintain a close attention to volume, size and gradation of aggregates as shown in Figure 5.1.

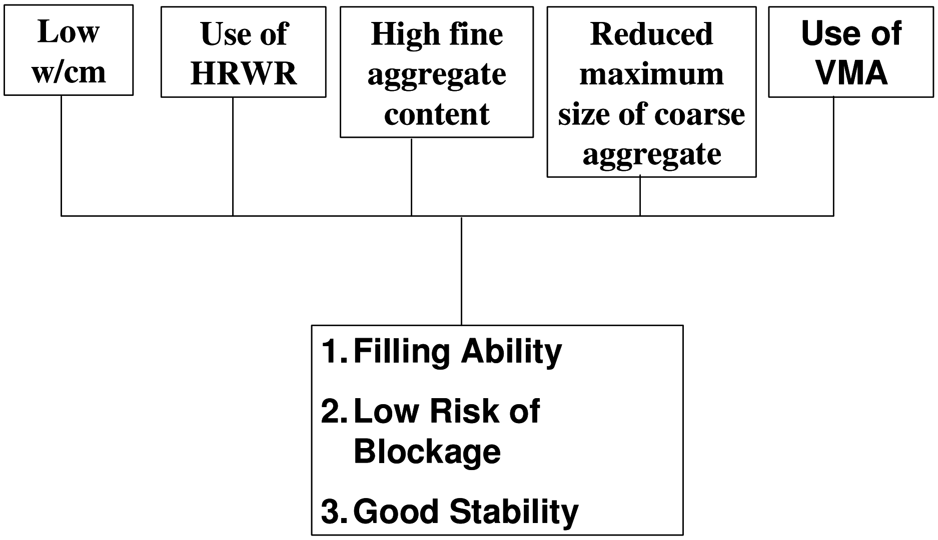


Figure 5.1 Principles of formulation of SCC (Adopted from (Khayat & Daczko, 2002))

In this chapter, the results of the development of mixture proportions for RSSCC and the fresh and hardened properties of selected concretes produced in the laboratory are presented. The RSSCC was developed using polycarboxylate-based HRWR, Type-III portland cement, silica fume (SF) and micro-fine fly ash (MFA). The fresh concrete properties measured included slump flow, T50 flow time, Visual Stability Index (VSI), V-funnel flow time, L-box passing ratio and air content. The hardened concrete properties measured included rate of compressive strength development, resistance to freezing and thawing, cracking potential and slant shear bond strength.

5.2 Analysis of Stage 1

About 40 mixtures were prepared in Stage 1, of these only 28 mixtures are discussed in this section. The rest of the 12 mixtures are not discussed since these mixtures exhibited either excessive segregation or very low slump flow. The main goal of this stage was to develop a correct mixing sequence using mortar mixer and pan mixer and to gain an idea about the optimum aggregate content, cementitious content to develop stable SCC or RSSCC. The fresh concrete properties tested for Stage-1 mixtures were primarily slump flow and VSI followed by setting time for those mixtures in which accelerators were added. Compressive strength at the age of 6 h or 24 hours was determined only for those mixtures which exhibited a VSI of 0 or 1.

Table 5.1 Selected parameters of Stage 1

MIXTURE #	MIXING TIME*	TYPE OF ADDITION OF HRWR	FINE AGGREGATE AS % OF TOTAL AGGREGATE VOLUME	VSI	T_{50} FLOW TIME (S)	COMPRESSIVE STRENGTH @ 24 H (MPA)
1	M7	1	64.9	3	5.6	--
2	M7	2	64.5	1	5.5	11
3	M7	2	58.1	1	5.3	13
4	M7	1	66.9	3	5.0	--
5	M7	1	64.3	2	6.0	16
6	M4.5	1	64.3	2	7.0	20
7	M4.5	1	64.3	2	7.5	23
8	M3.75	2	64.3	1	8.3	32
9	M18.5	1	64.3	0	7.2	31
10	M5.25	2	64.3	1	6.5	23
11	M5	2	59.4	3	3.4	--
12	M5	2	64.3	3	4.5	--
13	M7	2	42.6	3	4.0	--
14	M7	2	49.2	3	4.0	--
15	M5	2	54.1	2	6.5	23
16	M5	2	64.9	0	6.0	33
17	M5	1	64.9	2	7.0	28
18	P7	2	44.0	2	4.4	19
19	P7	2	44.0	2	4.0	17
20	P7	2	54.2	1	6.4	21
21	P7	2	54.2	0	7.2	23
22	P11	2	44.0	0	5.0	14
23	P7	2	54.2	0	6.5	25
24	P7	2	49.0	3	5.4	--
25	P5	2	59.3	3	5.2	--
26	P5	2	59.2	3	6.0	--
27	P3.5	2	50.5	2	6.5	17
28	P3.5	2	54.8	2	6.5	20

**-M-MORTAR MIXER AND P-PAN MIXER*

Table 5.1 and Figure 5.2 give the slump flow results, T50 flow time and the VSI ratings for all the mixtures used in this study. It can be observed that the mixtures that can be defined as stable (VSI 0 or 1) include Mix 2, 3, 8, 9, 10, 11, 16,18, 19, 20 and 21. The slump flow for these mixes is above 510 mm except in case of Mix 18. The VSI values for the remaining mixtures are either 2 or 3. The slump flow for the mixes with VSI 2 or 3 was measured as the flow of the solid materials only and any bleed water, if present, was not considered in the measurement. (Refer Appendix-B for pictorial presentation of different mixtures exhibiting VSI condition of 0, 2 and 3). Appendix-A gives detail observation of the mixture characteristics in the fresh state for all Stage-1 mixtures.

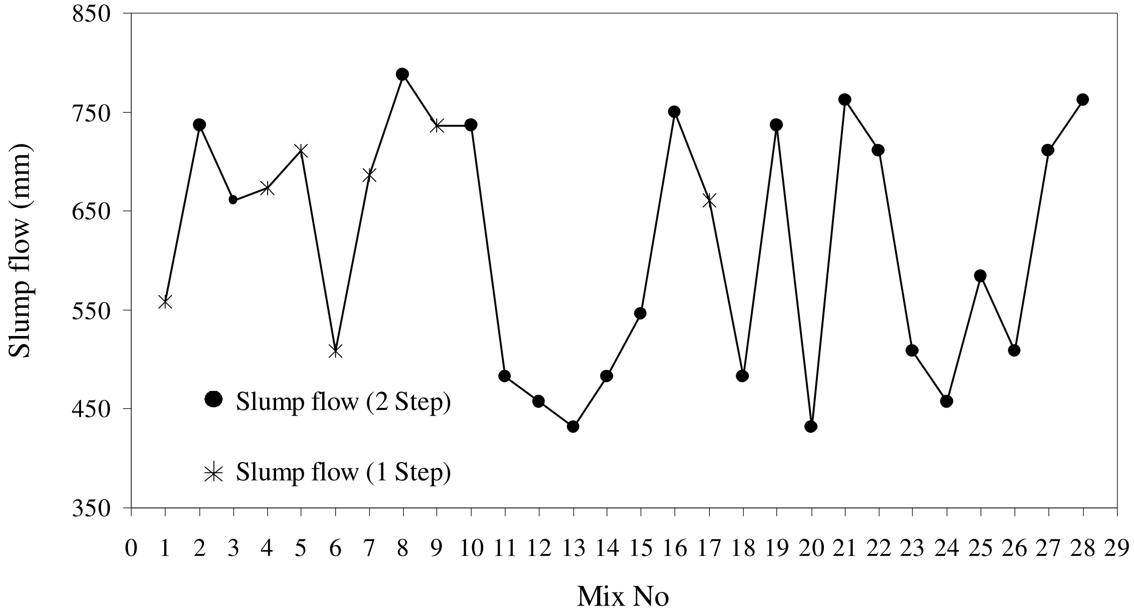


Figure 5.2 Slump flow of all Stage-1 mixtures

Comparing Table 5.1 and Appendix-A it can be observed that all the mixtures that have a VSI of 0 or 1 have a cementitious content between 480-540 kg/m3. For those mixtures mixed in the mortar mixer (Mix 1 through Mix 17) the VSI is 0 or 1 for mixtures containing 64-65% sand as percentage of total volume of aggregate, except for Mix 3 which has 58.6% sand as percentage of total volume of aggregate. Amongst mixtures mixed in pan mixer it is observed that those mixtures which have 54% sand as percentage of total volume of aggregate are stable mixtures except for Mix 22.

Mix 11 through 15 are some of the mixtures that were not stable and also had low slump flow values in comparison to the requirements. These mixtures had varying cementitious content (350 to 484 kg/m3) but the water content was almost constant and varied between 180 to 188 kg/m3. The reasons for failure of these mixtures could be one of the following:

- Low Cementitious Content
- Presence of cement as the only fine binder content except in case of Mix 15
- For Mix 11, 13 and 14 Type I cement was used which has lower fineness than Type III cement
- High Water Content
- Low Sand Content as a percentage of total volume of aggregate

Comparing Mixes 1 through 10, it was observed that those mixes which contained only cement as the cementitious component (Mix 1 to 4) required longer mixing times to achieve a visible flow as compared to Mix 6, 7 and 8, irrespective of the method of addition of superplasticizer. This confirms the results of earlier work by Chopin et al.(Chopin et al., 2004) who observed reduction in mixing time by about 40% due to increase of fine particle content and use of silica fume. By comparing data from

Appendix A and Table 5.1 it can be observed that for mixtures mixed in mortar mixer addition of silica fume also increased the stability of the mix. For mixtures prepared in pan mixer Mix 20 through 23 were stable mixtures and have a cementitious content of 485 kg/m3 with silica fume content of 34 kg/m3 and sand content of 55% as percentage of total volume of aggregate except for Mix 22 which had sand content of 44% as percentage of total volume of aggregate.

It can be observed that 2-step addition of the superplasticizer results in greater stability of the mixture, especially in case of mixtures prepared in mortar mixer as compared to the addition of the superplasticizer in a single dose (refer Table5.1). In Mix 1 through 4 the mixing time after addition of all the superplasticizer was kept constant and under these conditions Mix 2 and 3 achieved better stability and lower VSI than Mixes 1 and 4 (Refer Table 5.1). Mix 7 through 10 had similar mixture proportions (refer Appendix A) with differences in mixing sequence. For Mix 8 and 10 the VSI was 1 whereas for Mix 7 it was 2. The flowability and cohesiveness of the mixtures can be attributed to the time and amount of addition of superplasticizer. Figure 5.3 and Figure 5.4 show the slump flow obtained for mixture prepared by the 1-Step and 2-Step process of addition of superplasticizer. Figure 5.5 shows the percentage of mixtures normalized with the total number of mixtures which were stable and unstable using the two methods of addition of HRWR. There were more mixtures which were stable when the 2-Step process was adopted as compared to the 1-Step process.

Figure 5.3 Cement clumps observed in mixture prepared using 1-Step process

Figure 5.4 Mixture prepared using 2-Step process

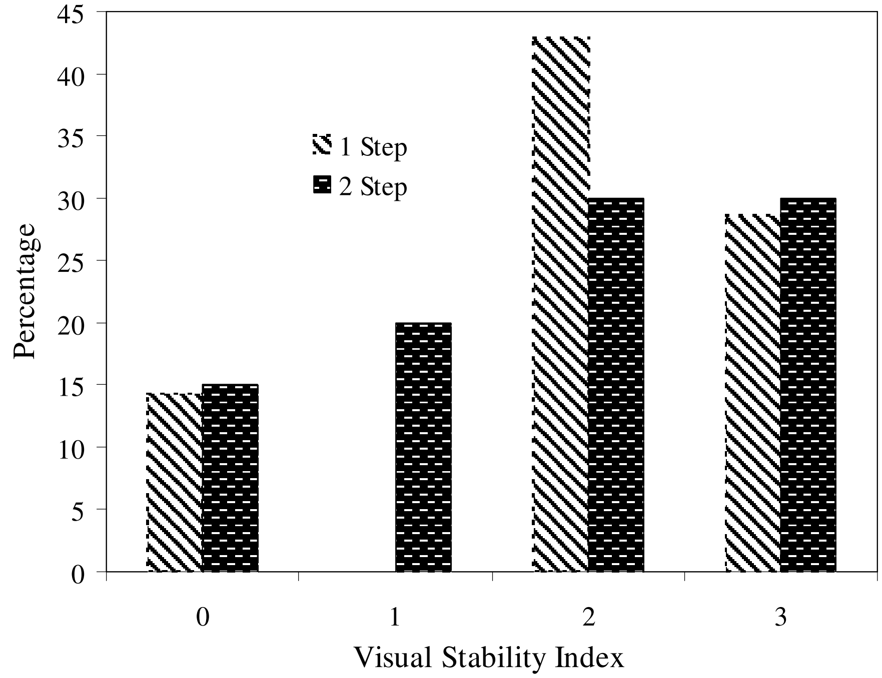


Figure 5.5 Stability of mixtures using different method of addition of HRWR

As mentioned in Appendix A, Mix 1 and 4 exhibited presence of many clumps shown in Figure 5.3. Also some of the mixtures (Mix 2, 11, 12) which were prepared using the 2 Step process for addition of superplasticizer exhibited presence of a few clumps (2 to 3) of unmixed cement. This could be attributed to the sequence of addition of sand. In these mixtures, though the 2-Step process was adopted, sand and pea gravel were added in the beginning of the mixing process. (Refer Table 3.8 of Chapter 3). Hence, in Mix 4 through 10 addition of pea gravel was followed by mixing for some period of time after which addition of sand was carried out. Thus, for Mix 4 through 7 clump formations could be purely due to the delayed addition of HRWR by adopting the 1-Step process.

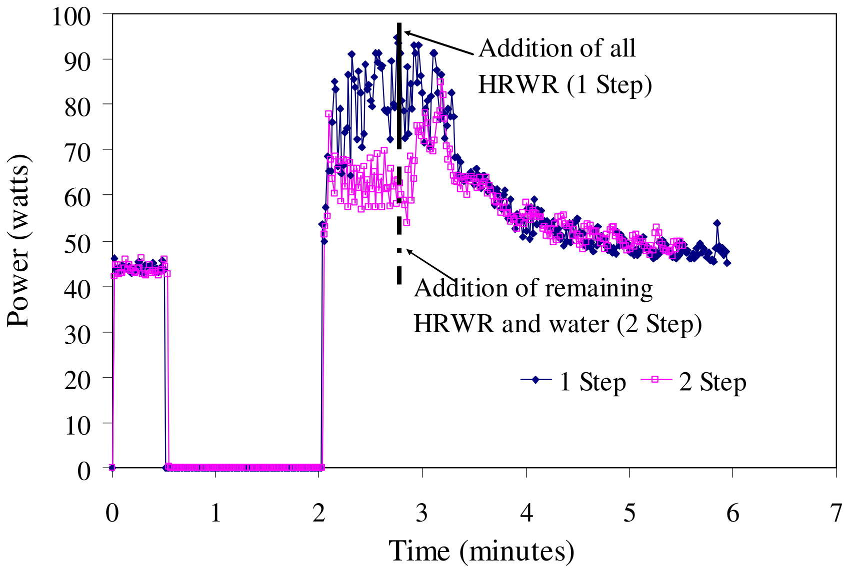


Figure 5.6 Power consumption curves of the mortar mixer for Mixture # 16 and 17

Mixture proportions of Mix 16 and 17 were identical and were actually the mixture proportions for the final RSSCC. The development of the mixture proportions is discussed in the following sections. The two mixtures were prepared to observe the power consumption of the mixer for the 1-Step and 2-Step method of addition of HRWR. No difference in the power consumption is observed at the beginning of the mixing process since same amount of pea gravel (SSD condition) was added. But after the addition of sand, cement and water (depending upon the method of addition of HRWR adopted), a difference in power consumption using the two methods is distinctively observed. The 2-Step process of addition of HRWR requires lower amount of power for mixing as compared to 1-Step process. Once all the mixing has taken place, the curves are almost identical (after 3.5 minutes in Figure 5.6).

The action mechanism of superplasticizers involves dispersion of agglomerates of cement particles especially in mixtures containing low water to cement ratio. Due to the effective dispersion the fluidity of the cement paste in the mixture increases. Dispersion of cement particles by polycarboxylate acid-based admixture is of steric hindrance type. A polycarboxylate acid-based admixture is a nonionic surface active agent with zero potential. Dispersion occurs due to the side chains of polyethylene oxide extending on the surface of cement particles in the form of a brush resulting in steric hindrance of the side chains. Initial addition of HRWR in 2-Step process facilitates the dispersion of cement particles from the time of addition of water to the cement. This helps in increasing the fluidity of mixture as indicated by the low power consumption after the first addition of ½ water and ½ HRWR (Refer Figure 5.6). Whereas, in case of 1-Step process initial addition of all the mixing water with cement results in lower dispersion of cement particles since the amount of mixing water is less due to low w/cm. Agglomerates of cement particles are formed in the initial stage in 1-Step process and later addition of HRWR results in lower dispersion of the cement particles.

As mentioned in the earlier section on scope of the project (See Chapter 1, Section 1.2) mixtures were prepared with the primary aim to develop RSSCC. The final setting time of the mixtures was measured for only those mixtures for which setting occurred within 7 hours after initial mixing.

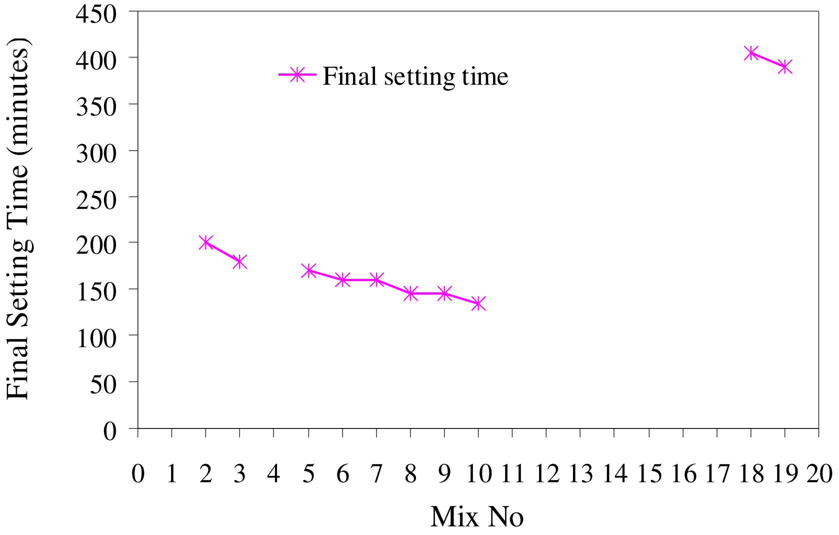


Figure 5.7 Final Setting Time for Mixtures in Stage 1

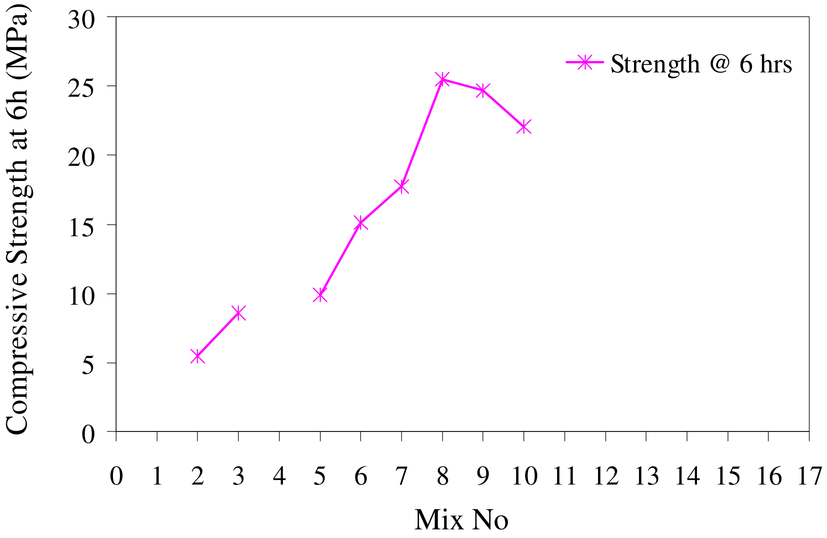


Figure 5.8 Compressive strength of mixtures in Stage 1

The final setting time and the compressive strength at 6 h are shown in Figures 5.7 and 5.8. Evaluating Figures 5.8 and 3.8 it can be observed that to achieve the desired compressive strength of 17 MPa at 6 h, set accelerator dosage of 20 kg/m3 is required. Lower dosages of set accelerator resulted in lower values of compressive strength at 6 h. Mixes 8 to 10 exhibited all the desired properties for RSSCC in terms of slump flow, stability and compressive strength (refer to Figures 5.2 and 5.8 and Table 5.1). These mixtures exhibited a slump flow of more than 680 mm with a VSI index of 0 or 1 and compressive strength of more than 21 MPa at the end of 6 h. These mixtures have a high cementitious content of about 540 kg/m3 (refer to Figure 2), a superplasticizer dosage of 9.0 kg/m3 and an accelerator dosage of 20.1 kg/m3. The additional fresh concrete properties tested for Mix 8 through 10 were V-funnel flow time, L-box passing ability and air-content. Table 5.2 gives the details of these properties.

Table 5.2 Fresh concrete properties of Mix 8 through 10

MIX NUMBER	**V-FUNNEL (S)**	**PASSING ABILITY (H_2/H_1)**	**AIR-CONTENT (%)**
8	16.0	0.68	6.5
9	13.0	0.71	4.5
10	14.2	0.73	6.5

One of the primary issues with these mixtures was the high amount of air voids observed on the surface of hardened concrete. Also some amount of air popping was observed in the fresh state (refer Appendix A). To resolve this issue, the manufacturer's of the chemical admixtures used in this project were consulted. As per discussions with them, the HRWR used was changed and Glenium 3400 was adopted for the next stage of mixtures.

5.3 Effects of Variation in Silica Fume Content (Stage 2)

In this stage, mixtures were produced with variation in silica fume content. Mix 8 was used as the basis for developing the different mixture proportions in this stage. In this section, results pertaining to silica fume variation of 0, 5, 7.5 and 10 % by mass of cement (475 kg/m3) are presented. In reality, mixtures containing silica fume in 1, 2 and 4 % were also prepared. The results of these mixtures are presented in Appendix C but are not utilized for analysis in this section since the compressive strength of these mixtures at 6h was nearly 6-7 MPa lower than the target compressive strength of 17 MPa. Table 5.3 gives the details of the test results for slump flow, VSI, L-box passing ratio and compressive strength at 6 h for the first series of mixtures involving variation in silica fume content. As explained in section 3.4.2.1, the amount of water added was varied as the function of moisture content of aggregates. However, for all these mixtures the total water content based on aggregate being in SSD condition was kept constant at 160 kg/m3, i.e. the w/c was kept constant.

Table 5.3 Properties of Step-1 mixtures

Mixture SET	**Silica fume (%)**	**Added water content (kg/m^3)**	**VSI**	**Slump flow (mm)**	**L-box passing ratio (H_2/H_1)**	**Compressive Strength @6h (MPa)**
I	0	176	0	660	0.85	9.0
	5	160	0	620	0.77	12.7
	7.5	161	0	585	0.70	15.9
	10	171	0	710	0.66	17.0
II	0	182	1	750	0.88	8.6
	5	175	0	635	0.85	10.6
	7.5	170	0	635	0.75	14.8
	10	185	1	750	0.71	16.9

The effects of variation of added water are discussed initially, followed by the discussion of the effects of addition of silica fume. The HRWR dosage was varied between 1.38 to 2.0% based on percentage of silica fume (Refer Table 3.8). Since the HRWR content was constant for SET I and SET II mixtures, it is assumed that the variation in the slump flow for mixtures with identical silica fume content occurred due to variation in extra water added to the mixtures to account for variation in aggregate moisture content. All mixtures produced in Step 1 were visually stable i.e. they did not exhibit any segregation or air popping and had a VSI of zero, except for two mixtures in SET II which had a VSI of 1.

The SET II mixture with no silica fume exhibited some amount of segregation and formation of a small mortar halo around the slump flow patty. The mixture with 10% silica fume exhibited some amount of air popping from the concrete patty during the slump flow test.

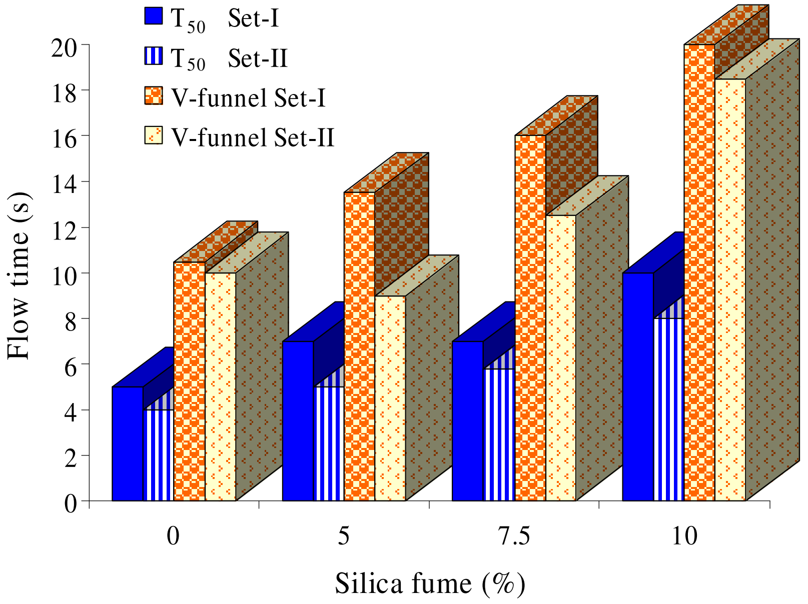


Figure 5.9 Flow time values for variation in silica fume content

Figure 5.9 gives the results of the T50 and the V-funnel flow time tests for all Step 1 mixtures. SET I mixtures had higher T50 flow time values as compared to SET II mixtures due to the higher amount of free water present in the latter. The V-funnel flow time values for SET I and SET II mixtures do not show significant variation for 0% and 10% of SF for an increase in added water. However, there is marked difference in the V-funnel flow time for the SET I and SET II mixtures, with 5 and 7.5% SF content with the drier aggregate (SET II) showing a shorter time. This is clearly a reflection of the higher amount of water added to these mixtures.

The L-box passing ratio values (see Table 5.3) also indicate that SET I mixtures have lower filing ability than SET II mixtures. The compressive strength at 6 hours was higher for SET I mixtures as compared to SET II mixtures (see Table 5.3).

In the part of the analysis presented below the effect of variation in the silica fume content is discussed. The T50 time values increased as the amount of silica fume in the mixtures is increased (see Figure 5.9). Similarly, the V-funnel flow time values show a progressive increase (from 10 s to 20 s) as the silica fume content in the mixture is increased (see Figure 5.9). The only exception is the mixture with 5% SF in SET II, for which the V-funnel flow time is 9 s. For mixture containing 10% silica fume, the V-funnel flow time and the T50 flow time continue to be on the higher side in comparison to the rest of the mixtures, indicating that higher amount of silica fume reduces the flowability of the mixtures. The L-box test indicates the passing ability of RSSCC mixtures and serves as an important test to assess the deformability of concrete. The acceptable limit is set to lie within 0.8 to 1.0 by the EFNARC guidelines (The European Guidelines for Self-Compacting Concrete, 2005). The passing ability values from L-box test are reduced as the silica fume content is increased for both sets of mixtures. All tests conducted for assessing the flowability of RSSCC discussed in this paragraph indicates that the deformability of RSSCC reduces as silica fume content is increased. On the other hand, the 6 hours compressive strength (Table 5.3) increases (from 9.0 MPa to 17.0 MPa) with the increase in SF percentages.

Due to the satisfactory level of compressive strength at 6 hours (17.0 MPa) and acceptable slump flow of 660 mm, the mixture with 10% SF from SET I was adopted as the base mixture for the next series of mixtures involving variation in accelerator dosage.

5.4 Effect of Variation in Accelerator Dosage (Stage 3)

As discussed in Section 3.4.2.1 of Chapter 3, in Stage 3 the amount of accelerator was varied between 4.7 and 9.1% by mass of cement. Mixtures with 8.8 and 9.1% of accelerator required lower dosages of HRWR, as compared to the other mixtures, to achieve target slump flow values (refer to Table 5.4).

Table 5.4 Properties of Stage 3 mixtures with variation in acclerator dosage

ACCELERATOR DOSAGE (%)	**SLUMP FLOW (MM)**	**COMPRESSIVE STRENGTH AT 6 H (MPA)**
4.7	726	15.5
5.3	717	16.3
6.9	744	16.8
7.5	749	16.5
8.5	749	17.3
8.8	711	18.0
9.1	705	18.2

Figure 5.10 shows the variation in the initial setting time (IST) and final setting time (FST) as the amount of accelerator is increased. Figure 5.10 suggests that a reduction in the dosage of HRWR coupled with an increase in the accelerator dosage reduces the setting time, which alleviated the higher early age strength as indicated in Table 5.4. Hence, for Stage 4 of the RSSCC mixture development process, the base

mixture proportion contained 9.1% accelerator, 10% SF and 160 kg/m3 of total water content.

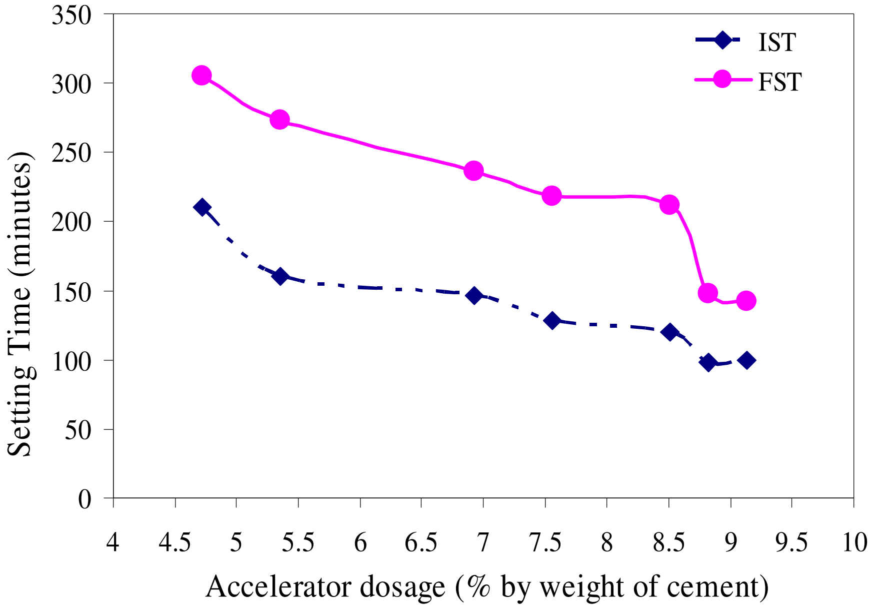


Figure 5.10 Variation in accelerator dosage

5.5 Variation in Micro-Fine Fly Ash Content (Stage 4)

In the Stage 4 of RSSCC mixture development, the micro-fine fly ash was added to help to reduce the loss of fluidity due to presence of silica fume. Most of the mixtures prepared in the earlier stages exhibited a large amount of surface pores on hardened concrete specimens. In an attempt to improve the surface quality of the RSSCC mixture and to make an effort to reduce amount of HRWR required to achieve target flowability micro-fine flyash was added to mixtures in Stage 4. A total of two mixtures were produced using the mixture proportions given in Table 3.9. The results obtained for

Stage 4 are given in Table 5.5. It can be seen that using 10% of SF in combination with 7.5% of MFA results in mixtures with reasonable flowability and compressive strength values. For both mixtures (Mixture 1 and Mixture 2) the addition of MFA increased the flowability as compared to the mixtures not containing MFA (compare Figure 5.9 and Tables 5.3 and 5.5). This increase is most likely related to the spherical shape of MFA which helped in lubricating the particles of cement and silica fume, thus improving the total fluidity of the mixture. Due to the higher value of compressive strength achieved, Mixture 2 from Step 3 (10% SF and 7.5% MFA) was used for evaluation of the HRWR dosage in Stage 4 of the mixture design process.

Table 5.5 Properties of mixtures with addition of MFA

Property	**Mixture 1 (10%MFA and 7.5% SF)**	**Mixture 2 (7.5% MFA and 10% SF)**
Slump flow (mm)	670	711
VSI	0	0
V-funnel flow time (s)	13	16
L-Box	0.8	0.77
Compressive Strength @ 6h MPa	16	19

5.6 Variation of HRWR Dosage (Stage 5)

In the final (Stage 5) part of the mixture design process, the effect of variation in the dosage of HRWR on the fluidity of the mixture was evaluated in an attempt to determine the optimum amount of superplasticizer needed. Figure 5.11 shows the variation in slump flow at different dosage levels of HRWR.

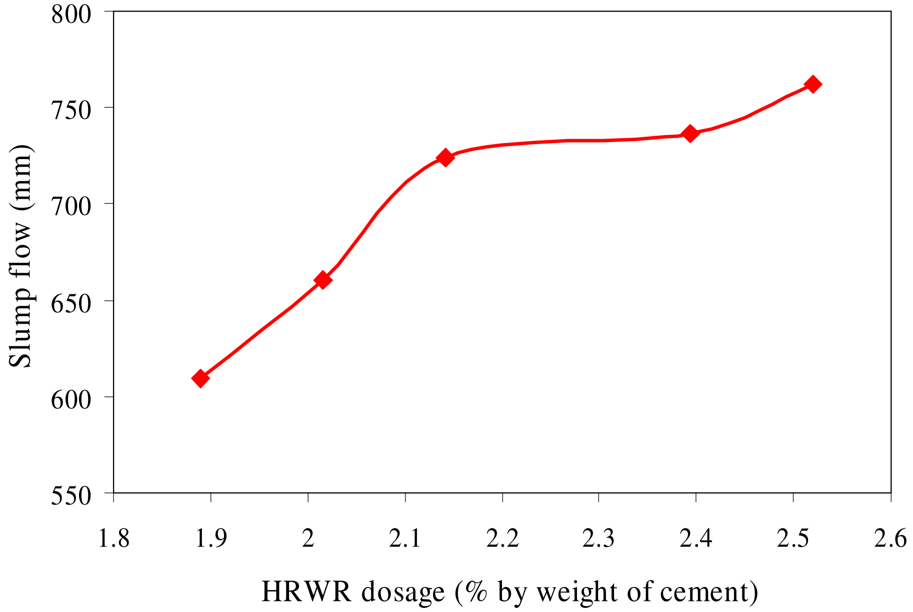


Figure 5.11 Variation in Slump Flow

The slump flow is below the target value of 660 ± 25 mm for lower HRWR dosages but increases rapidly beyond 2.15 % of HRWR addition.

Figure 5.12 gives the T50 and V-funnel flow time values for variation in HRWR dosage in the range from 1.88% to 2.53%. Both tests were carried out within 10 minutes after completion of the mixing process. In general, the incorporation of HRWR reduced the flow time, but the effects on T50 and V-funnel values were different. As seen in Figure 5.12, the initial increase in the HRWR dosage (from 1.88% to 2.05%) reduced the V-funnel flow time from 26s to 20s. However, the same increase in dosage of HRWR did not reduce the T50 flow time. Negligible change in T50 flow time can be attributed to two factors- operator precision and a mixture containing high cementitious content with small size aggregate.

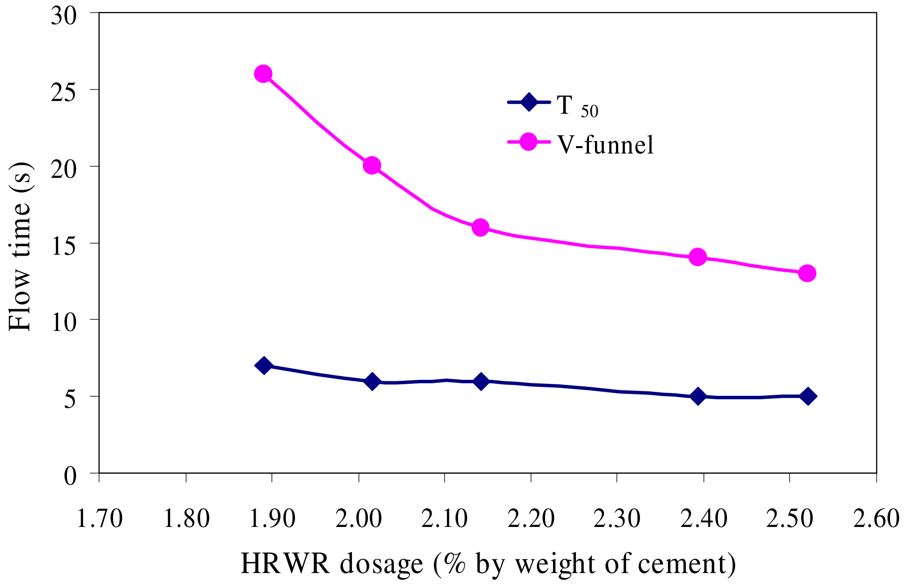


Figure 5.12 Flow time for variation in HRWR dosage

The observed trends in the V-funnel curve can be considered as analogous to the trends obtained in the mini-slump cone test used for determination of the HRWR saturation point (Aïtcin, 1998). The saturation point reflects the point for HRWR dosage beyond which further addition of the dispersing agent does not yield any considerable increase in the fluidity of the mixture.

When the HRWR dosage was increased beyond 2.52% by weight of cement, the mixture experienced severe segregation and bleeding. As a result, the V-funnel test could not be carried out. It appears, therefore, that the HRWR saturation point for RSSCC mixtures is between 2.1% and 2.4% by the weight of cement.

5.7 Fresh and Hardened Properties of RSSCC

The fresh properties of the RSSCC mixture prepared using the final mixture proportions obtained after carrying out all four steps discussed earlier are given the in Table 5.6.

Table 5.6 Fresh concrete properties of RSSCC

Property	**Value**
Slump flow	711 mm
VSI	0
T 50	6.0 seconds
V-funnel	16
L-box	0.8

The slump flow was 52 mm above the target slump flow of 660 mm. The mixture was visually stable and had a VSI of 0. Although the obtained V-funnel flow time (16 s) could be considered to be on a high side, the L-box passing ratio of 0.8 can be considered to be well within the acceptable range (Domone, 2006).

The hardened concrete properties of this mixture were as follows:

- Compressive Strength at 6 H 19.5 MPA and at 24 H was 30 MPA.
- Rapid Chloride Permeability – The test was carried out on samples cured for 28 days and the total charge measured was 1100 Coulombs. As per ASTM C 1202 this value indicates that the tested concrete has high resistivity to chloride ions ingress.
- Freeze-Thaw Durability – The change relative modulus over 300 cycles is shown in Figure 5.13. The durability factor was 98% at the end of 300 cycles

(as per ASTM C 666 Procedure A) indicating excellent freezing and thawing resistance. The change in relative modulus over two successive readings is low and the overall drop in relative modulus over 300 cycles is about 2%.

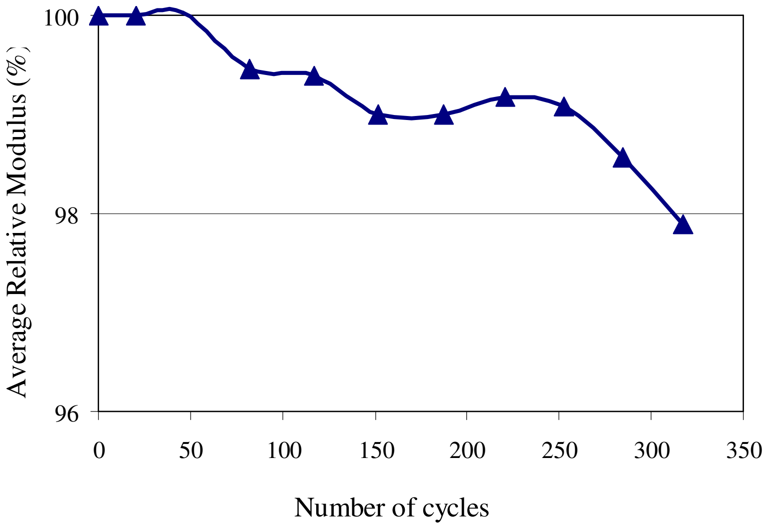
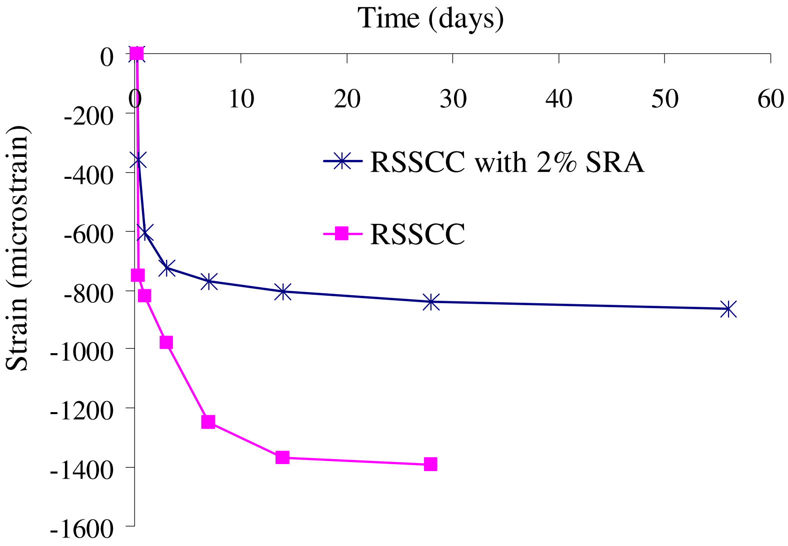


Figure 5.13 Variation in average relative modulus over 300 cycles

- Slant Shear Bond Strength – The slant shear bond strength values were 11.3 MPA at 24 H and 20.5 MPA at 7 days. These values are above the requirements of 7 MPA and 17 MPA, respectively, given in ASTM C 928 for rapid setting materials.
- Drying Shrinkage- Figure 5.14 shows the drying shrinkage strain developed for RSSCC specimens prepared with and without shrinkage reducing admixtures (SRA). RSSCC mixture containing 2 % SRA was prepared for studying the shrinkage characteristics. It was observed that the drying

shrinkage strain at 28 days was well within the allowable limits (1500 microstrains) of ASTM C 928 For mixture prepared with 2 % SRA. For mixture not containing any SRA the drying shrinkage strains at 28 days was about 100 microstrains below the allowable strain specified by ASTM C 928.



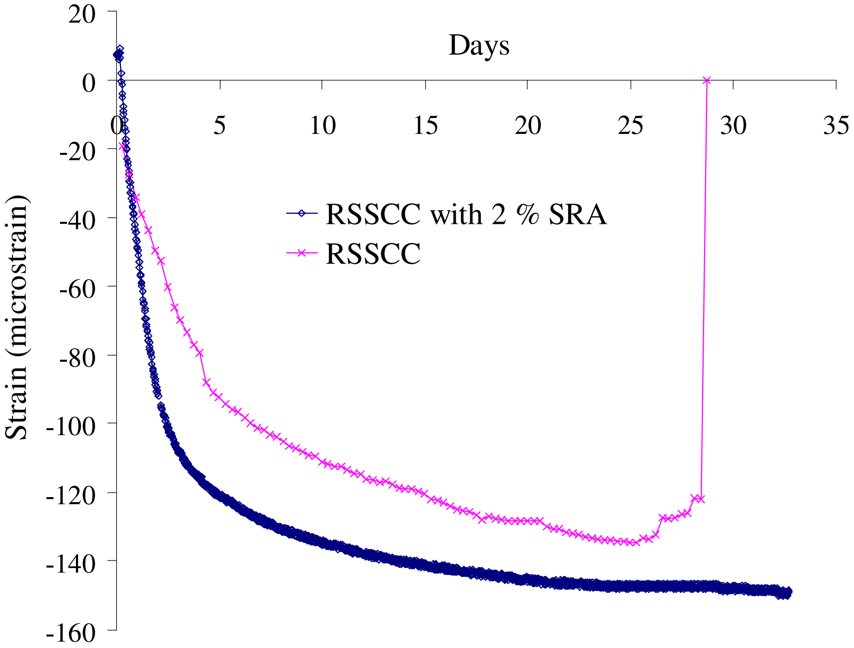


Figure 5.14 Drying shrinkage of RSSCC over 28 days

Figure 5.15 Development of strains in restrained shrinkage test

Figure 5.15 shows the strains developed for RSSCC mixture with and without SRA using the restrained ring test as per ASTM C 1581. It was observed that the strains developed in the RSSCC mixture with 2 % SRA were higher than those developed in RSSCC without SRA. The higher strains for mixtures containing SRA could be attributed to the interaction of set acclerator and the SRA. The samples without SRA developed cracks at 28 days. As per ASTM C 1581, the potential for cracking is moderate to low if the time of cracking is equal to 28 days.

CHAPTER 6 SENSTIVITY OF RAPID-SETTING SELF-CONSOLIDATING CONCRETE TO PRODUCTION PARAMETERS (PHASE II, STEP 2)

6.1 Introduction

It has been observed (Emborg, 2000; Nishizaki et al., 1999) that SCC is more sensitive to any deviation from target mixture or from mixing technique than ordinary concrete. Due to high cementitious content, self-consolidating concrete (SCC) typically requires longer mixing time compared to normal concrete, which can lead to reduction in the capacity of the concrete plant and can cause supply bottlenecks at the site (Lowke & Schiessl, 2005). Some of the recent studies (Deshpande & Olek, 2005; Emborg, 2000) indicate that the main factors influencing the robustness of production of SCC include:

- Type of mixing equipment,
- Length of mixing time and the sequence of addition of different types of admixtures,
- Total water content in the mixture as well as the amount of the free moisture ,
- Variations (within the specified limits) of aggregate grading curve.

The stability of SCC mixture is defined as its ability to retain uniform distribution of all its solid materials and not exhibit bleeding. The existing literature mentioned in Chapter 2 on SCC clearly indicates that its stability, in terms of flowability and segregation resistance, can be significantly influenced by the content as well as by physical and chemical properties of the component materials. At a repair jobsite, typically the volumes of materials used are small in comparison to a new construction jobsite. The likelihood of variation in aggregate moisture content is very high at a repair jobsite. Due to presence of higher volume of sand in comparison to normal concrete and presence of smaller size aggregate (Dmax= 9.5 mm) the aggregate moisture content would play an important role in the fluidity of RSSCC. Due to increase in specific surface area of coarse aggregates the amount of surface water present on aggregates if they are wet is high. The apparent increase or decrease of free water in the mixture can affect the slump flow retention of the mixture. The mixing action and mixing time will also affect the dispersion of all the constituents due to the changes in the amount of free water available for mixing due to variation in aggregate moisture content. This chapter presents the results of laboratory investigation on the sensitivity of rapid-setting self-consolidating concrete (RSSCC) to raw material and production variables that included: aggregate gradation, aggregate moisture content, the type of the mixer and remixing after a period of rest.

6.2 The Effect of Variation in Aggregate Moisture Content and Mixer Type (Group I)

6.2.1 Mortar Mixer

Presented in this section are the test results dealing with the influence of aggregate moisture content (sand and coarse aggregate) and type of mixing equipment on the fresh and hardened properties of Group I mixtures. The mixture proportions adopted in this study are presented in Chapter 3 (Table 3.11). To examine the effect of variability of aggregate moisture content in RSSCC, mixtures with w/cm of 0.31 and 0.36 were prepared. The study will help to evaluate the extent of effect of variation in free water on the slump retention and segregation resistance of RSSCC mixtures. The results for mixtures prepared in mortar mixer will be presented first, followed by the results of mixtures prepared in the pan mixer (section 6.2.2).

Figure 6.1 illustrates the variations in slump flow for different aggregate conditions prepared in the mortar mixer at two different water-cementitious ratios. Table 6.1 provides additional test results for these mixtures including, VSI, L-box passing ratio and the air content. As seen in Figure 6.1, the slump flow values for w/cm of 0.31 mixtures exhibit variation from 673 mm for 2 x SSD condition to 787 mm for DRY condition of aggregates. For mixture with w/cm of 0.36, the slump flow variation was between 711 mm to 787 mm for the different aggregate moisture conditions.

These results indicate that the reduction in the amount of actual mixing water added affects the slump flow to a larger extent for lower w/cm than for the higher w/cm. As discussed section 3.5.8 of Chapter 3, the acceptable deviation of slump flow value from that at SSD condition was + 25 mm. For w/cm of 0.31 the slump flow values for 2 x SSD condition and DRY condition of aggregates did not fall within the stipulated target range and were, respectively, 38 mm above and 76 mm below the SSD value (see Table 6.1).

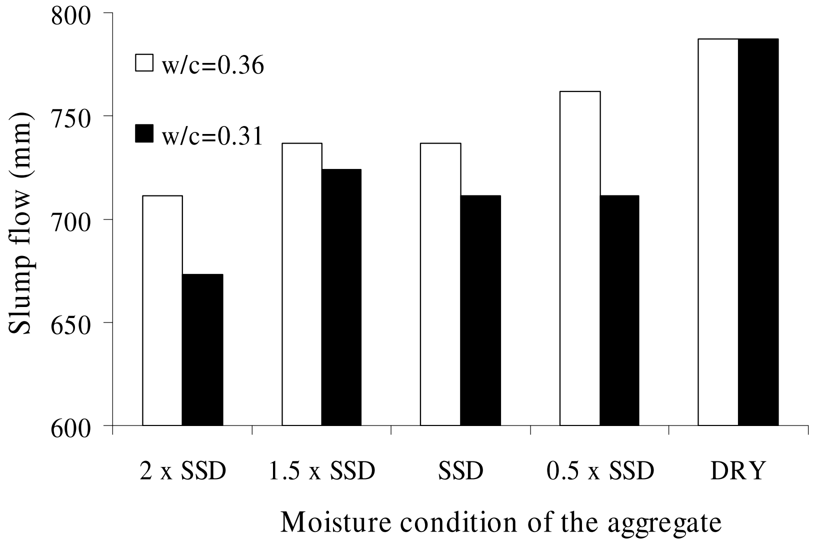


Figure 6.1 Slump flow of mixtures mixed in mortar mixer

Table 6.1 Fresh concrete properties of Group I mixtures mixed in mortar mixer

AGGREGATE CONDITION	***FREE W/CM***	**ACTUAL WATER ADDED (KG/M^3)**	**VSI**	**L-BOX PASSING RATIO**	**AIR-CONTENT (%)**	**DEVIATION OF SLUMP FLOW FROM SSD SLUMP FLOW (MM)**
W/CM= 0.31						
2 X SSD	0.281	160	0	0.74	5	38
1.5 X SSD	0.292	168	0	0.77	3.7	-13
SSD	0.311	176	0	0.8	5	0
0.5 X SSD	0.325	184	0	0.82	4	0
DRY	0.379	202	1	0.84	4.5	-76
W/CM= 0.36						
2 X SSD	0.312	176	0	0.82	5.1	25
1.5 X SSD	0.344	195	0	0.83	5.1	0
SSD	0.360	204	0	0.85	5.3	0
0.5 X SSD	0.375	213	0	0.87	--	-25
DRY	0.408	231	2	0.88	5.2	-51

Mixture with w/cm of 0.31 and aggregates at 2 x SSD condition was stiff in comparison to mixture with SSD aggregates whereas mixture with aggregates in dry condition had low degree of flowability. For w/cm = 0.36 the slump flow for all the aggregate conditions was within the stipulated target of 736 + 25, except for mixture with DRY aggregates. The VSI of all the mixtures with w/cm of 0.31 and 0.36 was zero except for those mixtures with aggregates in the dry conditions (see Table 6.1).

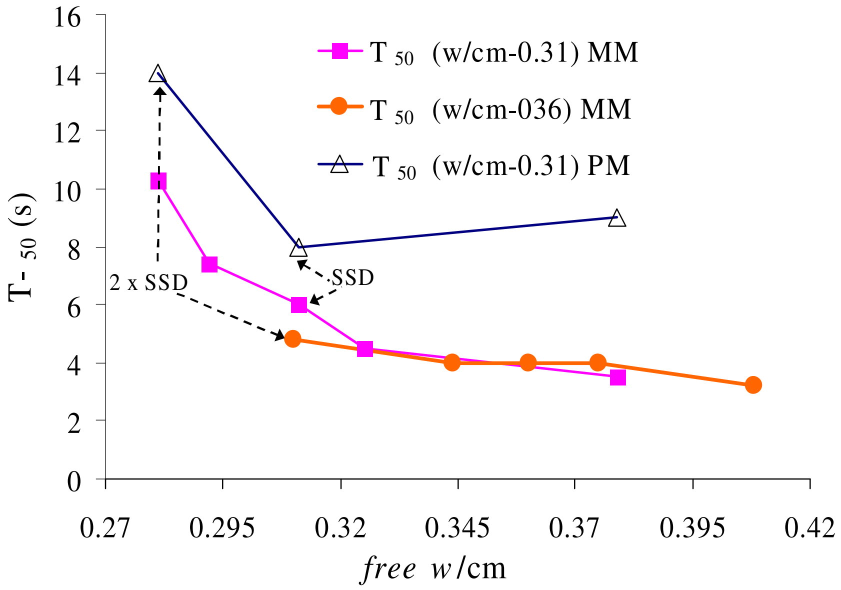


Figure 6.2 T_{50} flow time for Group I mixtures mixed in mortar mixer (MM) and pan mixer (PM)

Figure 6.2 shows the T50 flow time values plotted versus the free w/cm. The T50 flow time values indicate a trend similar to that observed for the slump flow. The mixtures with 0.31 w/cm and wetter aggregates (i.e. 2 x SSD) have a high T50 flow time value (10.3 s) as compared to the flow time of mixtures in SSD condition (6.0 s). This indicates that the mixture with 2 x SSD aggregates was stiffer as compared to mixture with aggregates in SSD condition. The T50 flow time values do not vary significantly for mixtures with w/cm = 0.36. The large variation in slump flow and T50 values for mixtures with w/cm of 0.31 indicate that excess water adsorbed on the aggregate surface incase of wet aggregates such as 2xSSD condition was not fully available to participate in lubricating the concrete. The gradual decrease in T50 flow values for mixtures with w/cm of 0.31 indicates that decrease in amount of free water added increased the fluidity due immediate availability of water. For mixtures prepared with dry aggregates the high deviation of slump flow values from those of mixtures with SSD aggregates for both w/cm indicates that the water added to the mixtures to account for water absorption of aggregates is not absorbed by the aggregates. The extra water results in segregation of mixtures as indicated by high VSI values.

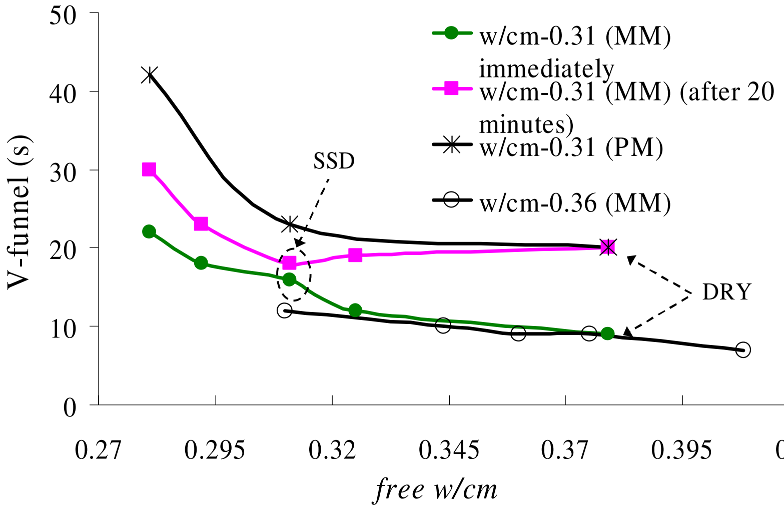
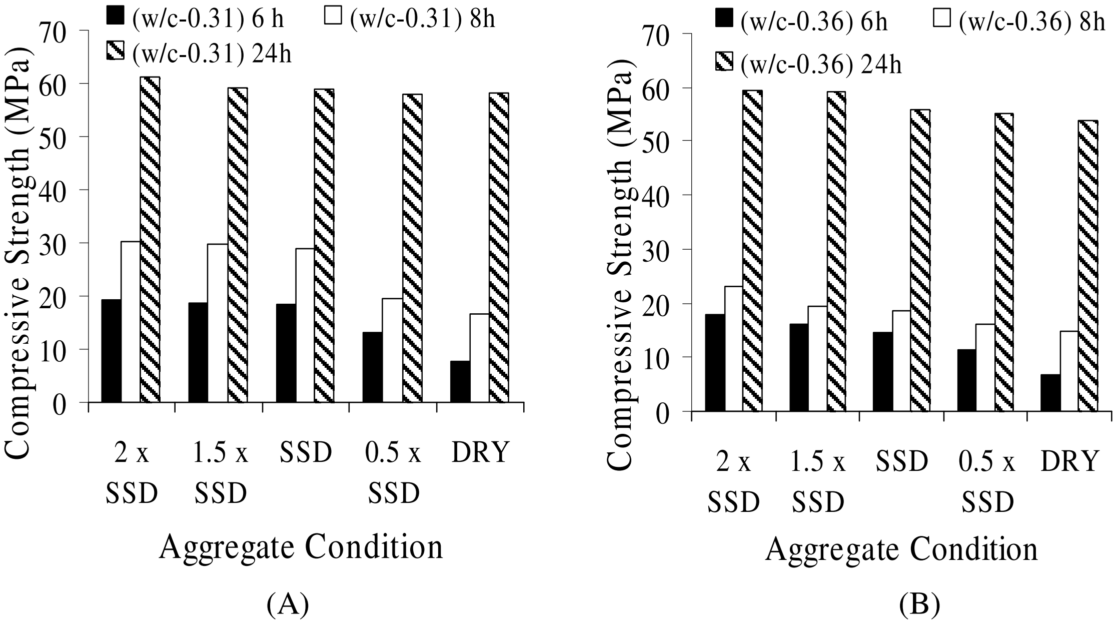


Figure 6.3 V-funnel flow time for Group I mixtures

The V-funnel flow time values for mixtures made at different w/cm and in two different mixers are shown in Figure 6.3. The V-funnel flow time for mixtures made with w/cm of 0.31 and prepared in the mortar mixer was determined either immediately after mixing or 20 minutes after mixing. It can be seen (Figure 6.3) that the V-funnel flow time for mixture with dry aggregates increases from 9 s (when measured immediately after mixing) to 19 s (when measured 20 minutes later). For the same time interval, the increase is only 2 s (from 18 s to 20 s) for mixtures with aggregates in the SSD condition. The increase in the V-funnel flow value observed for DRY aggregates indicates that the aggregate started absorbing the free water from the mixture after some interval rather than being absorbed in the beginning when added to the mixture resulting in loss of fluidity.

Mixtures with w/cm of 0.36 prepared with aggregate at different moisture conditions did not have large variations in the V-funnel flow time as compared to mixtures with w/cm of 0.31. The L-box passing ratio values (see Table 6.1) vary from 0.74 to 0.84 for mixtures with w/cm of 0.31 and from 0.82 to 0.88 for mixtures with w/cm of 0.36. For only one of the mixtures (2 x SSD, w/cm = 0.31) was the deviation from the L-box passing ratio value for SSD condition greater than 0.05.



(A) (B)

Figure 6.4 Compressive strength for mixtures (a) w/cm 0.31 and (b) w/cm 0.36

The rate of compressive strength development over 24 h for mixtures with w/cm of 0.31 and 0.36 is illustrated in Figures 6.4a, and 6.4b, respectively. The trend in the rate of strength development is similar for both w/cm. The compressive strength of mixtures with 0.31 w/cm varies between 19.3 MPa (2 x SSD aggregate condition) to 7.6 MPa (DRY aggregate condition). The 6 h compressive strength of 0.36 w/cm mixtures was 17.4 MPa. At 24 h all mixtures with 0.31 w/cm had nearly the same compressive strength of 60 MPa while the compressive strength of the mixtures with w/cm of 0.36 showed slight decrease in strength with an increase of the “free” water content in the mixture.

Figures 6.5 and 6.6 illustrate the power consumption of the mortar mixer obtained during mixing of w/cm of 0.31 and 0.36 mixtures, respectively.

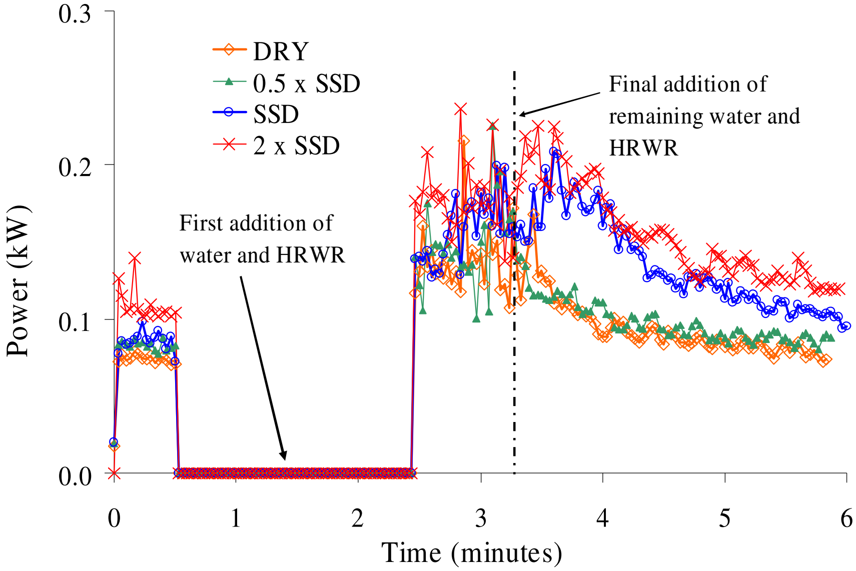


Figure 6.5 Power consumption curves for mixtures with w/cm = 0.31 mixed in mortar mixer

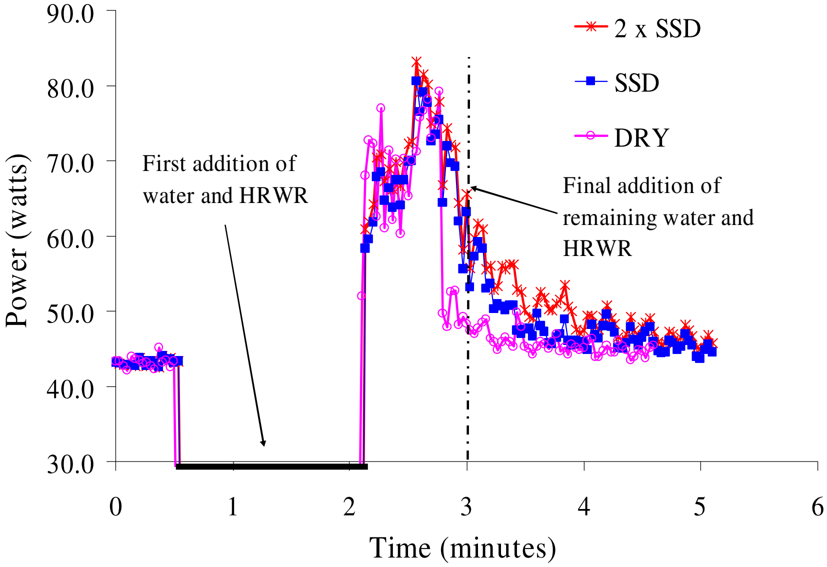


Figure 6.6 Power consumption curves for mixtures with w/cm = 0.36 mixed in mortar mixer

As explained in the section on mixing methodology, two different ampprobes were used to measure current variations during mixing mixtures. Despite differences in the sensitivity of these probes, the trends in the power curves for both of these mixtures are similar.

Comparing the power consumption data for mixtures made with 0.31 w/cm obtained for varying aggregate moisture conditions (Figure 6.5), it can be seen that the power consumption is highest for mixture with aggregates in 2 x SSD condition (less free water) and it is lowest for mixture made with DRY aggregates. All RSSCC mixtures made with w/cm of 0.31 showed significant variation in the power consumption after addition of all the water and HRWR has taken place (see Figure 6.5). The power consumption-time curves obtained during the 3-5 minutes mixing period for mixtures with aggregates in 2 x SSD condition and SSD condition exhibit steeper slope than the same curves for mixtures with aggregates with 0.5 x SSD or 0 % moisture. All curves become relatively flat after about 4 minutes of mixing, indicating that mixture components have been more or less uniformly distributed throughout the volume of the mix and thus implying the end of the mixing process. The main conclusion that can be formed on the basis of these results is that as the free water to cementitious ratio decreases from 0.379 to 0.281 the time required for the mixtures to achieve uniform dispersion of components decreases.

For mixtures with w/cm= 0.36 (see Figure 6.6) the time required to achieve uniform mixing is shorter (between 3.15 minutes for DRY aggregate condition to 4.15 minutes for 2 x SSD condition) than that required by mixtures with w/cm = 0.31.

In Figure 6.7 the power consumption values for mixtures with w/cm=0.31 mixed in mortar mixture after addition of all ingredients has taken place is shown. Based on the regression analysis an equation for predicting the power consumption based on the moisture condition of aggregates can be developed for the ampprobe used and is given by the following equation:

POWER CONSUMPTION = 0.17 X A X E^ -0.0035

where, a = constant based on the aggregate moisture condition as a function of SSD condition.

Different values of 'a' which would be acceptable for this mixture and the ampprobe are provided in Table 6. Regression coefficients for all the curves shown in Figure 6.7 are also provided.

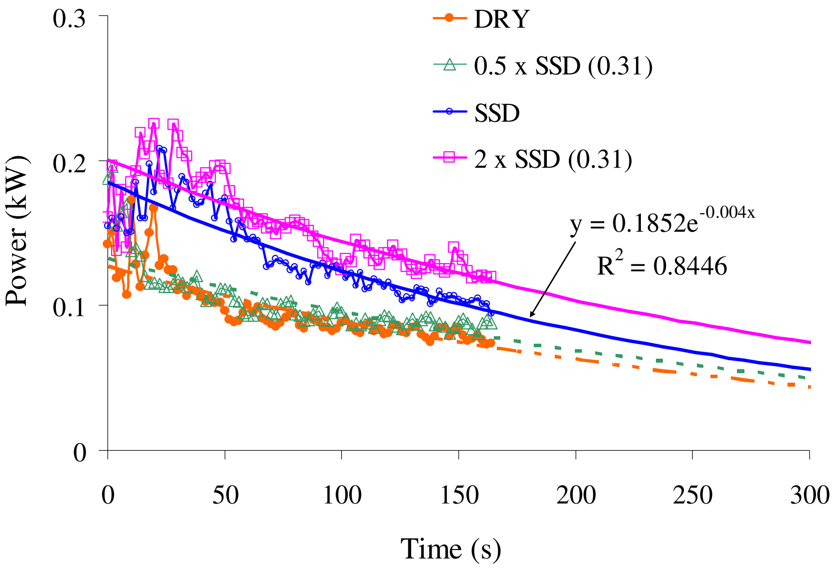


Figure 6.7 Regression analysis of power consumption data for w/c of 0.31

Table 6.2 Regression coefficients and constant 'a' for different aggregate conditions

AGGREGATE CONDITION	REGRESSION COEFFICIENT R^2	CONSTANT A
2 X SSD	0.75	1.176
1.5 SSD	0.77	1.117
SSD	0.85	1
0.5 SSD	0.70	0.882
DRY	0.76	0.76

6.2.2 Pan Mixer

So far, only the results pertaining to the mortar mixer have been presented. This section discusses the results obtained for the mixtures prepared in the pan mixer. The properties of these concretes (w/cm = 0.31) are given in Table 6.3.

Table 6.3 Properties of concrete mixtures (w/cm = 0.31) made in pan mixer

AGGREGATE CONDITION	*FREE W/CM*	SLUMP FLOW (MM)	VSI	AIR CONTENT (%)	L-BOX PASSING RATIO	COMPRESSIVE STRENGTH (MPA)	
						6 H	24 H
2 X SSD	0.281	610	0	2.3	0.65	15.3	56.8
SSD	0.311	762	0	4	0.71	17.6	60.1
DRY	0.379	750	1	3.9	0.75	9.2	56.2

As mentioned in Chapter 3 the mixtures mixed in pan mixer were prepared using aggregate with three different moisture conditions: 2 x SSD, SSD and DRY. The slump flow for these mixtures was between 610 mm to 750 mm and the difference in the slump flow value for mixture with 2 x SSD condition from that of mixture with aggregates in SSD condition was very large (152 mm). The VSI was zero for mixtures with aggregates in 2 x SSD and SSD conditions and the mixture with aggregate in DRY condition had the VSI value of 1. The T50 flow time value of the pan mixtures was higher in comparison to the mixtures prepared in mortar mixer, irrespective of the w/cm (see Figure 6.2). Similarly, for all three moisture conditions, the V-funnel flow time values (see Figure 6.3) were higher for all mixtures mixed in the pan mixer. The L-box values varied from 0.65 to 0.75 and were lower in comparison to mixtures mixed in the mortar mixer (see Tables 6.1 and 6.3).

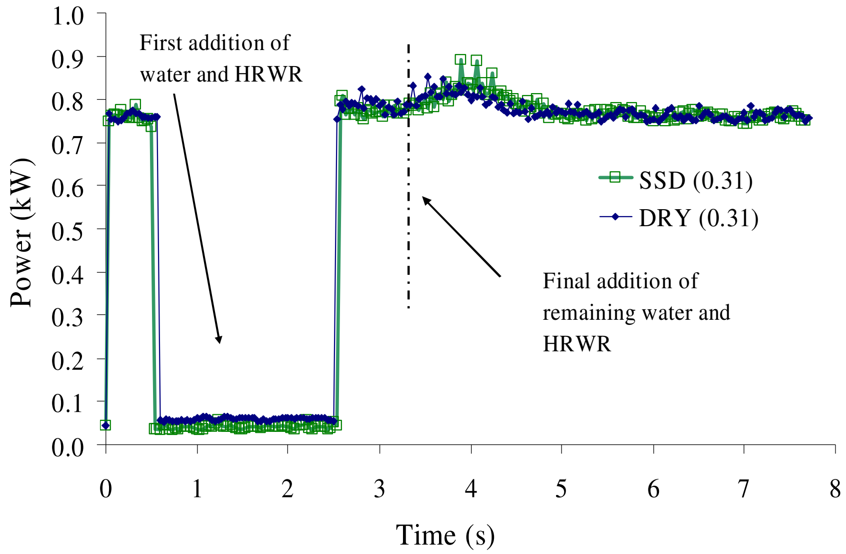


Figure 6.8 Power consumption curves for mixtures mixed in pan mixer

Figure 6.8 shows the power consumption curves for mixtures mixed in pan mixer. Contrary to what was observed for mortar mixtures (Figure 6.5), these curves do not show large variations in power consumption values as different ingredients are added to the pan mixer (i.e., at the point when final addition of remaining water and HRWR has taken place at the end of 3.45 minutes). Though the curves imply that a stable state has been achieved after addition of all water and HRWR, in reality the mixture had not achieved homogeneity. When the mixer was stopped after 5 minutes of mixing the presence of undispersed cement particles and clumps was observed. It took almost three minutes of additional mixing time before the homogenous dispersion of all ingredients was observed (compare Figures 6.5 and 6.8). This difference between the degree of dispersion achieved in the mortar mixer and pan mixer is most likely due to the differences in the mixing action provided by these two mixers.

The pan mixer has a vertical axis of rotation and consists of the rotating pan and rotating blades. The rotating action causes movement of the ingredients, which results in uniform mixing. However, due to a single axis of rotation, the mixture components have only one direction of movement. This results in low dispersion of all cementitious particles and reduced flowability. In the mortar mixer, the mixer has a horizontal drum with a rotating shaft to which two blades are attached. During the mixing action in the mortar mixer the concrete ingredients are subjected to dual actions – shear caused by the rotating blades and tumbling due to the free fall of mixture during turning of the paddles (see Figure 3.5a in Chapter 3). Due to this dual mixing action, the cementitious particles are probably better dispersed and, as a result, mixtures exhibit higher flowability. The difference in mixing action can also result in difference in the amount of HRWR absorbed on the cement particles (Vickers, Farrington, Bury and Brower, 2005). In the mortar mixer the blades revolve at a speed of 65 rpm whereas the speed of the pan mixer blades is 55 rpm. In this project the percentage of HRWR absorbed using different mixers was not carried out but it has been reported by Vickers et al. (2005) that the rate of dispersant depletion in the mixture is affected by the mixing speed.

6.3 Effect of Variation in Aggregate Gradation

The effect of variation in aggregate gradation was studied for six (Group II) mixtures. The properties of all mixtures in this group are compared with the properties of mixture prepared with Sand-1, PG-1 in SSD condition. Figure 6.9 shows the slump flow for Group II mixtures. It can be seen that none of the mixtures had a slump flow within the stipulated range of 711 + 25 mm.

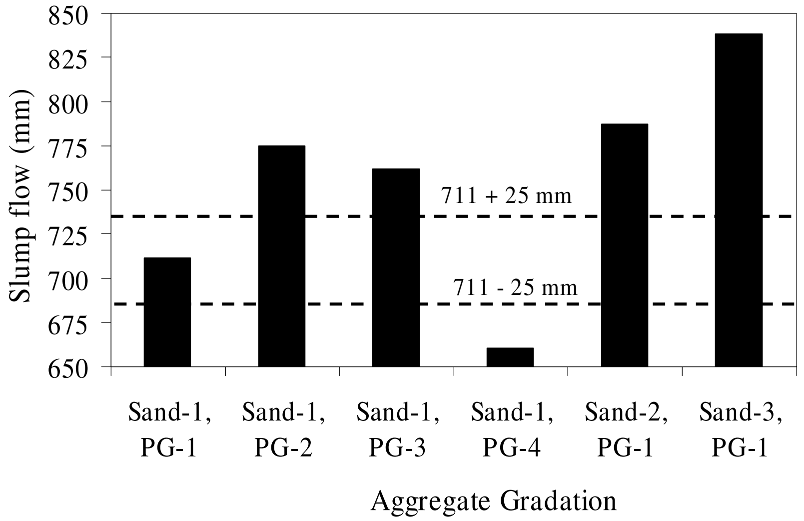


Figure 6.9 Slump flow for Group II mixtures

Table 6.4 lists the fresh concrete properties for Group II mixtures, including deviation of slump flow, VSI, L-box passing ratio and air-content values. The slump flow value increased by 64 mm when the PG-1 aggregate (FM=5.45) was replaced by PG-2 aggregate (FM=5.67). PG-1 and PG-2 aggregates differ in the amount of material passing sieve opening of 4.75 mm, with nearly 70% being retained on higher sieve sizes for PG-2 material. The T50 and the V-funnel values are slightly lower for mixture with

Sand-1 and PG-2 aggregates in comparison to Sand-1 and PG-1 mixture (see Figure 6.10). The 6 h compressive strength values for Sand-1 and PG-2 aggregates are slightly lower than the allowable deviation of (18.4 -2 MPa) (see Figure 6.11).

Table 6.4 Fresh properties of Group II mixtures

AGGREGATE GRADATION	**DEVIATION OF SLUMP FLOW FROM SAND-1, PG-1 MIXTURE SLUMP FLOW (MM)**	**VSI**	**L-BOX PASSING RATIO**	**AIR CONTENT (%)**
SAND-1, PG-1	0	0	0.8	4
SAND-1, PG-2	64	0	0.82	4.7
SAND-1, PG-3	51	1	0.79	4.2
SAND-1, PG-4	-50	0	0.72	4
SAND-2, PG-1	76	2	0.74	4.5
SAND-3, PG-1	127	2	0.75	3.2

Mixture prepared with Sand-1 and PG-3 aggregates was slightly unstable with a VSI of 1 and slump flow of 51 mm higher than that of mixture containing Sand-1 and PG-1 aggregates. The gradations of PG-1 and PG-3 are comparable up to sieve size 2.36 mm above which PG-1 has finer particles (see Figure 3.4 in Chapter 3). These slight variations also reduce the power consumption for mixture containing Sand-1 and PG-3 aggregates as compared to Sand-1 and PG-1 mixture (see Figure 6.12).

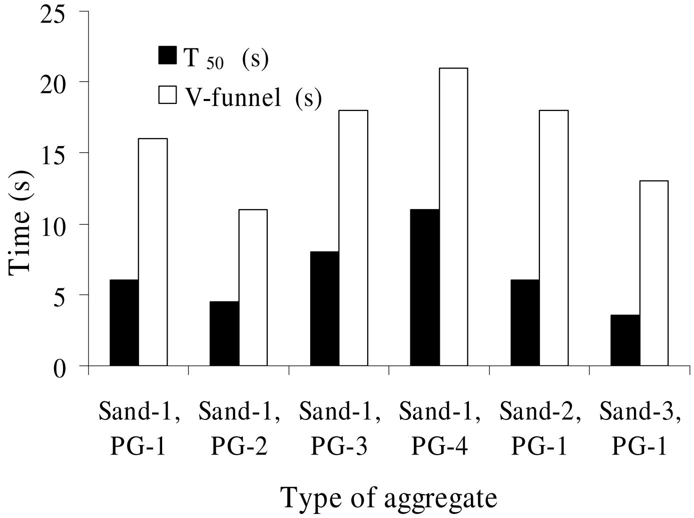


Figure 6.10 T_{50} and V-funnel flow time values for Group II mixtures

The PG-4 aggregate (FM = 6.05) was much coarser than the PG-1 aggregate (FM=5.45) and the use of this aggregate resulted in significant reduction of the slump flow of Sand-1, PG-4 mixture compared to the slump flow of Sand-1, PG-1 mixture (see Figure 6.9). The coarser mixture also exhibited high T50 and V-funnel time values (see Figure 6.10). The 6 h compressive strength of that mixture was very low in comparison with mixture containing Sand-1, PG-1 aggregates (see Figure 6.11).

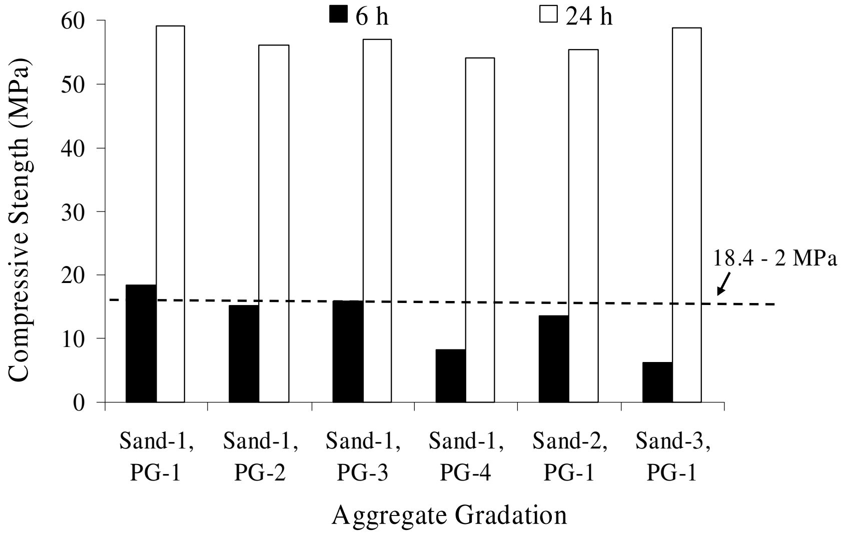


Figure 6.11 Compressive strength at 6 and 24 h for Group II mixtures

When the gradation of sand was changed by replacing Sand-1 (FM=4.14) with a finer Sand-2 (FM=3.87), the Sand-2 and PG-1 mixture exhibited tendency to segregate, as indicated by VSI = 2 (see Table 6.4). This mixture also had lower 6 h compressive strength than the mixture containing Sand-1, PG-1 aggregates (see Figure 6.11). The power consumption curve of this mixture is comparable to the mixture containing Sand-1, PG-3 aggregates (see Figure 6.12).

Mixture containing Sand-3 and PG-1 aggregates had the highest slump flow (837 mm) in this group of mixtures (see Figure 6.9). The T50 and V-funnel flow time values were also low (Figure 6.10) but with VSI = 2 this mixture also exhibited some amount of segregation.

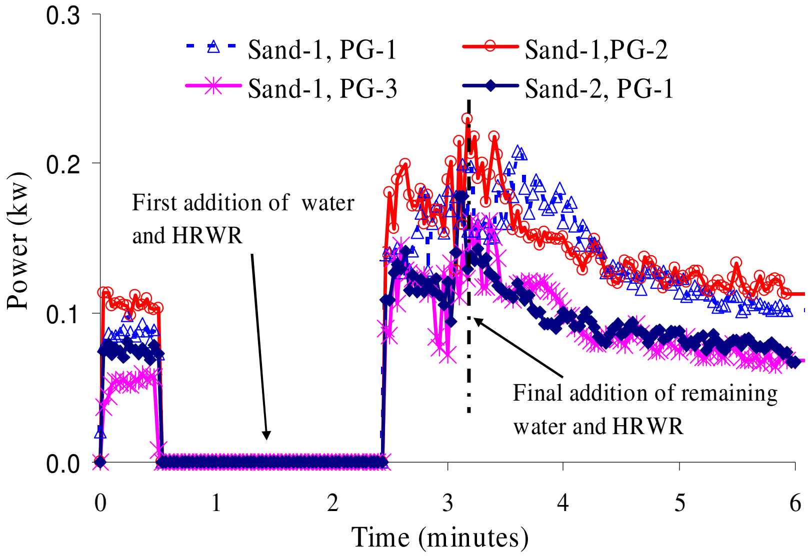


Figure 6.12 Power consumption curves for Group II mixtures

6.4 Effect of Re-Mixing on Properties of RSSCC

At many repair sites, especially when pavement repair is concerned, repair concrete may be needed to be supplied small amounts (sometimes only about 0.4 to 0.6 cu.ft) every few meters along the pavement. A typical example would be dowel bar retrofit repair where, dowels are inserted at mid-depth of the slab, perpendicular to the joint or the crack and the slots filled with repair concrete. For small applications, typically a small volume of concrete is prepared (about 1-1.5 cu.ft) every time but many a times all of the fresh concrete cannot be utilized at the same joint. In such cases the mixer is then moved to the next joint/crack which needs repair. Ideally, the concrete that has been sitting in the mixer should be discarded. To avoid such wastage of concrete, effect of re-mixing on RSSCC after a certain period of rest was evaluated.

As explained in Section 3.4.2.2 of Chapter 3, re-mixing of Group III mixtures was carried out after 10, 17 and 25 minute of rest. The mixtures were stored in the mixer during the rest period and the mouth of mixer was covered with a plastic sheet to avoid water loss by evaporation. Figure 6.13 shows the slump flow obtained by remixing RSSCC with w/cm = 0.31 at different rest-time intervals.

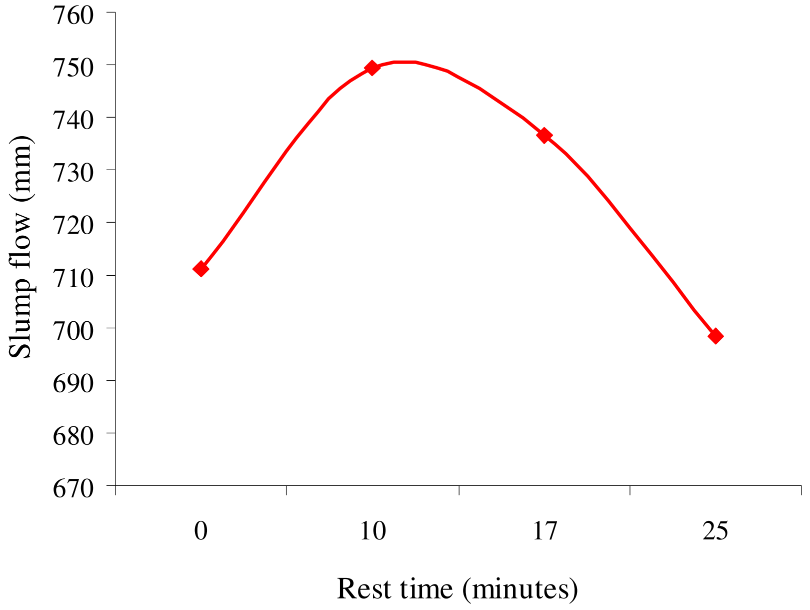


Figure 6.13 Slump flow after remixing for RSSCC w/cm = 0.31

The deviation of slump flow from zero rest interval, and other rest intervals is large for mixtures re-mixed after a rest of 10 and 17 minutes and is not within the criteria (+ 25 mm of the value obtained for mixture tested with zero rest interval). Large amount of air-bubbles and air-popping was observed after re-mixing was carried out at 10 minutes and 17 minutes of rest interval. All the mixtures exhibited a VSI of 1 due to the air popping when the rest period was more than zero minutes (refer Table 6.5).

Table 6.5 Flowability and passing ability for Group III mixtures

REST TIME INTERVAL (MINUTE)	**VSI**	**T_{50} (S)**	**V-FUNNEL (S)**	**L-BOX**
0	0	6.4	14.5	0.81
10	1	5.0	15.0	0.80
17	1	6.4	18.0	0.78
25	1	7.0	18.0	0.77

The flowability properties and passing ability of RSSCC for Group III mixtures is presented in Table 6.5. The V-funnel values are high for mixtures remixed after 17 and 25 minutes of rest indicating loss of fluidity. The fresh and hardened air-content for these mixtures is presented in Table 6.6.

Table 6.6 Fresh And Hardened Concrete Air Content For Group III Mixtures

REST TIME INTERVAL (MINUTES)	**AIR – CONTENT OF FRESH CONCRETE**	**AIR-CONTENT OF HARDENED CONCRETE**	**SPACING FACTOR (MM)**
0	5	5.3	361
10	4.5	3.4	354
17	3	2.9	421
25	2	2.3	485

The fresh and hardened air-content are reduced as the rest time is increased. The spacing factor is also increased.

CHAPTER 7: SUMMARY, CONCLUSION AND RECOMMENDATIONS

7.1 Summary

The basic tenet of this research was to investigate the early-age and long-term performance of commercial rapid-setting materials (CRSMs) and to develop a new repair material based on the principles of self-consolidating concrete. The new material was designed to overcome the problems of poor consolidation of CRSMs, especially when used in dowel bar retrofit (DBR) repair technique. In DBR technique the space underneath dowel bar is typically shallow, only about 12-13 mm. The confined space restricts the flow of concrete underneath the dowel bar thus increasing a potential for creating poor quality bond if concrete is of inadequate workability and is not properly consolidated. The overall width of the saw cut is also small (typically about 64 mm) which can provide difficulty in vibrating the repair concrete, again resulting in poor consolidation. Literature review indicated that the performance of DBR systems was affected primarily by insufficient or improper mixing, inadequate vibration, low rate of development of compressive strength and low freeze-thaw durability factor.

To evaluate the performance of repair materials for use in DBR technique, four different types of commonly used CRSMs were selected and tested during the Phase-I of the study. Flowability and rate of compressive strength gain in the first 24 h were the main criteria to determine the optimum aggregate (pea gravel) addition for the CRSMs. The consistency of CRSM mixtures was defined in terms of the spread of the slump patty (minimum of 482 mm) for this project. It was observed that when extended with pea gravel, all CRSMs required an additional amount of water to achieve the desired workability parameters. After fixing the pea gravel content, the performance of CRSMs at different temperatures was evaluated. The robustness of the repair concrete was vastly affected by the pre-conditioning temperature. It was observed that the repair materials investigated in this study have a wide range of values for all the properties for which the materials were evaluated. From this detail study it was observed that some of the CRSMs did not perform efficiently in terms of the desired rate of compressive strength gain over 28 days (as per ASTM C 928) or in terms of resistance to freezing and thawing. The cracking potential of all the CRSMs tested was low.

In the second phase of the research, RSSCC with a ternary blend of Type III cement, silica fume and micro-fine fly ash was developed in the laboratory. The coarse aggregate adopted had maximum size of 9.5 mm and was similar to that adopted as an extension aggregate when studying commercial rapid-setting materials. The chemical admixtures used in the study were high range water reducers, set-accelerators and air-entraining agent. Since repair concrete is prepared on site using small volume mortar mixers and small batch sizes, different mixing sequences were studied in detail to develop mixing sequence and mixing time for the preparation of stable and flowable RSSCC.

The development of mixture proportions for RSSCC is presented in detail in Chapter 5. The fresh concrete properties measured were slump flow, T50 flow time, Visual Stability Index (VSI), V-funnel flow time, L-box passing ratio and air content. The hardened concrete properties studied were the rate of compressive strength development, slant shear bond strength, and durability (using rapid chloride permeability and freeze-thaw resistance tests). The effect of the variations of production parameters on fresh and hardened concrete properties is presented in details in Chapter 6 . The production parameters studied were changes in aggregate moisture content, aggregate gradation, type of mixing equipment and re-mixing of the RSSCC after various periods of rest. Distinctive variation in power consumption by the mortar mixer was observed when the aggregate moisture content or the aggregate gradation was varied.

The summary of major findings of this from this study is presented in two sections. The first section (7.1.1) focuses on summary derived from Phase I that involved development of mixture proportions for CRSMs and evaluation of the effects of temperature of ingredients on early-age and long term properties. The second section (7.1.2) contains the summary drawn from Phase II of the study involving development of RSSCC and evaluation of sensitivity of RSSCC to production parameters. In section 7.1.3 a summary comparison of all the properties for CSRMs and RSSCC is presented.

7.1.1 Summary From Phase – I

1. All commercial rapid setting materials used in this project required some amount of extra water per bag of the repair mortar to achieve a spread of more than 480 MM (criteria as per Table 3.14) for the slump test. The highest amount of extra water was added for mixtures prepared with ThoRoc™10-60 for all pre-conditioning temperatures. The optimum pea gravel extension obtained for all the CSRMs was 60%, by mass of one bag of dry materials. ThoRoc™10-60 exhibited a strong sensitivity to initial material temperature and did not develop any noticeable spread for the slump test when prepared at 40°C.
2. The pre-conditioning temperature plays an important role in the setting time of the CRSMs which, in turn, affects the rate of compressive strength gain. All the CRSMs tested in this project achieved the required compressive strength set up for this project (13.5 MPA) at the end of 1 or 2 hours for pre-conditioned temperature of 23 and 40°C. The HDBR material achieved the target compressive strength of 35 MPA at the end of 24 H, as prescribed by ASTM C 928, for pre-conditioned temperatures of 23 and 40°C. FSHPC and ThoRoc™10-60 did not achieve the target compressive strength as specified in the ASTM C 928 at end of 24 H for materials pre-conditioned to 23 and 40°C, but were within the requirements developed for this project (above 27.5 MPA at end of 24 H). Set®45 R developed the required strength at early ages of 1 and 3 H, but did not meet the requirements of ASTM C 928 (nor those developed for the project) for 24 hours and at 28 days for all the pre-conditioning temperatures. For all the CRSMs evaluated at pre-conditioning temperature of 10°C, the setting time was high and the compressive

strength achieved at the ages of 1 or 3H was lower than the requirements. All the CRSMs achieved comparable strength at the end of 24 H for materials pre-conditioned at 10°C.

3. The slant shear bond strength at 1 and 7 days for all the CSRMs at different pre-conditioning temperatures was not within ± 15% of the value required by ASTM C 928.

4. All of the evaluated CSRMs, except, for Thoroc™10-60 have low freeze-thaw resistance for all the pre-conditioning temperatures. As compared to the requirements for durable normal concrete (5-6.5% of air voids), the air-content of hardened CSRMs is very low. ThoRoc™10-60 had high air content but also exhibited high spacing factor (545 μm). FSHPC exhibited the highest spacing factor and the lowest air-content. It also had the lowest durability factor and failed within 20 cycles of freezing and thawing.

5. Amongst all the materials, SET® 45 R exhibited the lowest drying shrinkage strain (185 μm) (initial measurement was taken at 3 H from the time of addition of mixing water) at 28 days for materials stored and cured at 23°C. For the same condition, HDBR had the highest drying shrinkage values (570 μm as measured at 3 H from the time of addition of mixing water). All CSRMs, except SET® 45HW exhibited low drying shrinkage for materials stored and cured at 40°C. The cracking potential (as per ASTM C 1581) for all the CSRMs tested for this project was low. None of the test specimens failed at the end of the test at the age of 60 days.

7.1.2 SUMMARY FROM PHASE-II

1. Rapid-setting self-consolidating concrete applicable for small batch volume repair jobs was developed using 9.5 mm maximum size pea gravel at the end of Phase I, of the project. The successful mixture incorporated ternary blend of type III Portland cement, silica fume and micro-fine fly ash. The total cementitious materials content was high (560 kg/m^3) and the mixture required high dosages of HRWR (2.15%) and accelerator (8.8%) as well as low water to cementitious ratio (w/cm 0.31).
2. Addition of silica fume helped to lower the mixing time for RSSCC. It enhanced the compressive strength at 6 H but reduced the passing ratio values (about 0.77) below the project requirements. To increase the deformability especially in terms of passing ability of RSSCC mixtures micro-fine fly ash was added. The passing ratio and the flowability were enhanced considerably by its addition. The amount of HRWR required was also reduced from 2.5% to 2.15% due to addition of micro-fine fly ash. Addition of high amount of polycarboxylate type of HRWR (2.5% by mass of cement) to increase fluidity of RSSCC resulted in segregation and bleeding.
3. The sequence of addition of HRWR affects the deformability of RSSCC. A 2-step addition of HRWR increases the flowability and the deformability of RSSCC in comparison to addition of HRWR during 1-step process.
4. The high content of cementitious materials and low w/cm resulted in RSSCC with low chloride permeability and a high resistance to freezing and thawing. High value of the slant shear bond strength at the age of 1 and 7 days indicates that this mixture is capable of developing good bond with the existing old concrete.

5. The cracking susceptibility for RSSCC mixtures without shrinkage reducing admixture (SRA) is moderate whereas addition of SRA reduced the cracking susceptibility to low.
6. This study highlights the potential impact of variations in aggregate moisture content and aggregate gradations on the stability and deformability of RSSCC mixtures. Variation in aggregate moisture content and aggregate gradation primarily affects the fresh properties of RSSCC and compressive strength at 6 hrs. The effect is more prominent for mixtures mixed in the mortar mixer as compared to those mixed in the pan mixer.
7. Presence of excessive water layer on the surface of aggregate does not facilitate the flowability of RSSCC. Mixtures made with aggregates in 2 x SSD condition exhibited the least favorable flow properties and deviated largely from the values obtained for RSSCC mixtures cast with aggregates in SSD condition.
8. Mixtures having w/cm of 0.36 were more robust and less sensitive to variations in aggregate moisture conditions than those made with w/cm of 0.31.
9. For mortar mixer, the power consumption curves provided useful information regarding the completeness of the mixing cycle. Prominent deviation in power consumption can be observed for mixtures made with very wet or dry aggregates.
10. The mixing action and the speed of revolution of the mixer blades affect the deformability and the flow properties of RSSCC mixtures. The dual mixing action of mortar mixers resulted in RSSCC mixtures exhibiting more favorable flow properties than mixtures made in pan mixers.

11. The dual mixing action of the mortar mixer also reduces the total mixing time for RSSCC mixtures since it facilitates better dispersion of cement particles. For the same mixture proportions, mixtures prepared in mortar mixers require shorter mixing time to achieve comparable fresh and hardened concrete properties than mixtures mixed in the pan mixer.
12. Reduction in fineness modulus of sand increases the flowability of the RSSCC mixtures but also increases their tendency to segregate.

7.1.3 Summary of Properties for Phase-I and Phase-II Mixtures

Table 7.1 presents a summary of the test results for CRSMs and RSSCC mixtures carried out during Phase I and Phase II of the study. The setting time and the compressive strength at 3 hrs was higher for CRSMs in comparison to RSSCC. The long term performance in terms of durability to freezing and thawing was excellent for RSSCC mixture whereas the CRSMs exhibited poor resistance to freezing and thawing. The study indicates that the choice of repair material (concrete) would depend upon the jobsite, quantity of material required and the time limit within which the pavement needs to be opened for traffic. Use of RSSCC might entail lane closure for extended period of time in comparison to CRSM due to longer final setting time but excellent resistance freeze-thaw damage of RSSCC would increase the long term performance of the repaired pavement. To avoid recurring costs of repair due to use of CRSMs as the patching material, a one time lengthy closure of lanes for repair using RSSCC might be justified.

Table 7.1 Summary of Properties for CRSM and RSSCC mixtures

PROPERTY	CRSMS	RSSCC
SLUMP FLOW/SPREAD (MM)	480-640	711
FINAL SETTING TIME (MINUTES)	18-40	180
COMPRESSIVE STRENGTH (MPA)		
3 H FOR CRSM AND 6 H FOR RSSCC	21	19
24 H	25-48	57
FREEZE-THAW DURABILITY	LOW, EXCEPT FOR THOROC™10-60	EXCELLENT
CRACKING POTENTIAL	LOW	LOW TO MODERATE
SLANT SHEAR BOND STRENGTH AT 1 DAY (MPA)	5.5	11

7.2 Recommendations for Usage of Repair Materials

In this section, recommendations for preparing repair concrete for use in DBR systems based on the findings of this study are provided. Section 7.2.1 pertains to the recommended performance criteria for CRSMs. It also gives information on material requirements and mixing procedures. Section 7.2.2 provides recommendation for using RSSCC for repair purposes.

7.2.1 Recommended Practices for Use of CRSMs

The CRSMs available on the market are manufactured by various manufacturers and have different chemical compositions. The extensive experiments performed during Phase-I indicate that each CRSM is unique in its performance. The fresh properties and early age properties of the CRSMs are vastly affected by changes in temperature. It is recommended that every CRSM be evaluated before being considered for DBR project. Currently, INDOT follows ASTM C 928 specifications for evaluating performance of CRSMs used in DBR projects. These specifications do not indicate the allowable aggregate content in the repair mortar. The suggested recommendations can be used as guidelines for preparing repair concrete using CRSMs for DBR purposes. For the purpose of preparing repair concrete using CRSM it is recommended that clean pea gravel (maximum size 9.5 mm) in SSD condition be used along with the CRSM. Clean potable water should be used for mixing. Warm water should be used for mixing carried out at lower temperatures (near 10°C) whereas for mixing performed at 40°C should contain cold water. The mixing process should be carried out in mortar mixer and the following sequence should be adopted:

PEA GRAVEL → MIX FOR 45 SECONDS → CRSM + WATER → MIX FOR 120 SECONDS

Table 7.2 gives the recommended values for performance of CRSMs using 60% pea gravel content per bag of repair mortar (1 bag = 22.7 kg). The recommendations provided in Table 7.2 are based on the results and evaluation of products used in this project. These recommendations need to be verified by studying the actual performance of different CRSMs in the field, as discussed in detail in section 7.3 of this chapter.

Table 7.2 Recommended performance characteristics for CRSMs used for DBR projects

PROPERTY	**TEST METHOD**	**TEMPERATURE**		
		10°C	**23°C**	**40°C**
SLUMP (MM)	ASTM C 143 (NO RODDING)	MINIMUM 480		
FINAL SETTING TIME	ASTM C 266 (GILMORE)	45	35	35
COMPRESSIVE STRENGTH	ASTM C 39			
1H		--	14	14
2H		--	14	14
3 H		10	21	21
24 H		20	28	28
28 DAYS		35	35	35
SLANT SHEAR BOND STRENGTH (MPA) **1 DAY**	ASTM C 882 MODIFIED BY ASTM C 928	7	7	7
7 DAYS		10	10	10
FREEZE-THAW RESISTANCE	ASTM C 666 PROCEDURE A	NOT LESS THAN 60% AT 300 CYCLES		
CRACKING POTENTIAL	ASTM C 1581	LOW		

7.2.2 Recommended Practices for Use of RSSCC

In this study RSSCC was developed using specific raw materials. The physical and chemical properties of every ingredient of RSSCC will affect the stability and deformability of the mixture. Since the mixture ingredients available at a particular job site will certainly not be the same as the ingredients used in this study, it is essential to carry to out detail physical and chemical analysis of all the before the start of the project. It is recommended that prior to start of the project, a thorough analysis of cement and HRWR compatibility be carried out to ensure retention of slump flow for the desired time frame. The recommended mixture proportions for RSSCC are given in Table 7.3. These mixture proportions can be varied by about 10% to accommodate changes in the physical and chemical characteristics of the constituents.

Table 7.3 Mixture proportion for RSSCC

Material	**Quantity**
Type III Cement (kg/m^3)	485
Micro-fine fly ash by weight of cement (%)	7.5
Silica fume by weight of cement (%)	10
w/cm	0.311
Polycarboxylate based HRWR (% by weight of cement)	2.15
Non-chloride accelerator (% by weight of cement)	8.88
Air-entraining agent (% by weight of cement)	0.02
Pea Gravel (kg/m^3)	581
Sand (kg/m^3)	928
Water (kg/m^3)	176

Clean washed pea gravel (nominal size 9.5 mm) in SSD condition and clean sand conforming to INDOT # 23 (also in SSD condition) should be used. The acceptable surface moisture of the aggregates (pea gravel and sand) should be ± 0.5 SSD i.e., the aggregates can either have 0.5 x SSD of surface moisture or 1.5 x SSD of surface moisture. The mixing should be carried out in the mortar mixer. The following mixing sequence should be adopted as a guideline for the mixing process:

Pea gravel + water (water required to bring the aggregate in SSD condition if it is not in SSD condition) → mix for 30 s → Sand + AE + cement + silica fume + MFA + ½ remaining water + ½ HRWR + accelerator→ 45 s → ½ remaining water + ½ HRWR→ 225 s

Mortar mixers of different motor power and volume are available in the market. To achieve a cohesive and stable RSSCC, it is recommended that trials be first carried out using the above mixing sequence before adopting it for a final mixture. The mixing times should be considered as guidelines and appropriate changes can be made, if required.

Table 7.4 shows the acceptance criteria for fresh and hardened RSSCC concrete. To evaluate the stability and deformability of RSSCC mixtures all the tests suggested for flowability and passing ability should be carried out. Some of the tests (such as T_{50} flow time or VSI) are very subjective and operator dependent. Hence, the values of these tests should not be considered as stand alone and other tests values should also be considered.

Table 7.4 Recommended criteria for RSSCC mixtures

PROPERTY	**TEST METHOD**	**RECOMMENDED CRITERIA**
FRESH CONCRETE PROPERTIES		
SLUMP FLOW	ASTM C 1611	710 ± 25 MM
T_{50} FLOW TIME	ASTM C 1611	6.0 ± 2.0 S
VSI	ASTM C 1611	0 OR 1
V-FUNNEL FLOW TIME	REFER SECTION 3.5.2	16.0 ± 3.1 S
L-BOX TEST	REFER SECTION 3.5.2	0.80 ± 0.05
AIR CONTENT	ASTM C 231	6.0 ± 1.0 %
FINAL SETTING TIME	ASTM C 403	180 ± 15 MINUTES
HARDENED CONCRETE PROPERTIES		
COMPRESSIVE STRENGTH (MPA)	ASTM C 39	
6 H		19 ± 2
8 H		28 ± 2
24 H		58 ± 2
FREEZE-THAW DURABILITY	ASTM C 666 PROCEDURE A	MORE THAN 60 % AT THE END OF 300 CYCLES
CRACKING POTENTIAL	ASTM C 1581	LOW TO MODERATE AT THE END OF 60 DAYS
SLANT SHEAR BOND STRENGTH (MPA)	ASTM C 882 MODIFIED BY ASTM C 928	11 MPA ± 2

7.3 Recommendations for Future Research

This section provides information on future research work necessary for proper utilization of repair materials and long term performance of repaired pavements. The section provides information on field implementation and verification of requirements proposed in section 7.3. Suggestions about addition of different ingredients to enhance the performance of CRSMs as well as RSSCC mixtures are discussed in details. The detailed recommendations for future work are as follows:

1. FIELD IMPLEMENTATION AND VERIFICATION OF PROPOSED RECOMMENDATIONS

As summarized in the previous sections, this research evaluated four CRSMs materials and developed new rapid-setting repair material based on the principles of SCC.

For the four CRSMs evaluated, mixing water above that recommended by the manufacturer was added to the repair materials. The criterion for slump has been changed to measurement of the spread of the slump patty instead of the height of the slump as prescribed by ASTM C 143. In this project, all the materials were evaluated in the laboratory under stringent quality control conditions. In spite of the strict control on measuring of material quantity, mixing time and proper adherence to test procedures, not all of the CRSMS reached the compressive strength at the end of 1 day stipulated by ASTM C 928 (35 MPa). The low strength development could be attributed to the addition of extra water. As explained in the Chapter 3, the addition of water was essential to achieve proper flow of the repair concrete underneath the dowel bar. To verify the recommendation of addition of extra water and evaluation of spread of slump and to assess long term field performance of DBR systems, it is critical to carry out field implementations of the selected four CRSMs. Field trials will also assist in verifying if the proposed recommendation for lower compressive strength values at 1 day will not affect the long term performance of the DBR installations.

This project studied the effect of initial temperatures on the performance of CRSMs. These studies were also carried out in the laboratory and though an attempt was made to keep the temperature conditions of the materials as close to jobsite as possible, the mixing process and preparation of specimens was carried out at 23°C for all the temperature conditions. It is suggested that field implementations at different temperature conditions should be carried out so that detail information on early-age properties and long-term performance of CRSMs will be available.

In the second phase of this project RSSCC mixture employing locally available materials was developed in the laboratory. In order to validate the laboratory conclusions, and to evaluate the performance of the new material, it is critical to perform a field trial implementation of the RSSCC mixture.

The long term performance of the DBR slots should be carried out for at least five years so that sufficient information on durability and load transfer ability of the DBR slot will be available. The durability of the repair material is affected by freezing thawing of the repair concrete, development of cracks due to plastic shrinkage and restrained shrinkage, chloride and water ingress, and abrasion due to traffic. It is essential to evaluate the in situ properties of DBR slot by using field techniques (e.g falling weight deflectometer) rather than only laboratory tests (e.g. resistance to freeze-thaw cycles, cracking potential). Information from the field tests will provide valuable insight into optimizing the long term performance of the repair concrete.

2. EVALUATION OF AIR VOIDS AND SORPTIVITY FOR DURABLE REPAIR CONCRETE

The air content of hardened concrete prepared by utilizing CRSMs was evaluated in this project. The percentage of air-voids, air-void spacing factor and resistance to freezing and thawing are three parameters that are closely linked in the case of normal concrete. It was observed that (at the given air content) the spacing factor was higher for concrete prepared using CRSMs in comparison to limits applied for normal concrete. The chemical composition of CRSMs is vastly different from the chemical composition of typical cements. Hence it can be speculated that the air-void limits used for normal concrete are not directly applicable to CRSMs. Since most of the materials tested in the project exhibited low freeze-thaw resistance, it recommended that allowable limits for air-void percentage and spacing factor be developed for CRSMs.

Typically, repair concrete is placed on old concrete in DBR techniques. The slot is prepared by saw cutting the damaged concrete or crack. The crack is cleaned using sand blasting or high pressure water jets. If any excess water is remaining in the slot, or if the pavement is opened for traffic before it has completely matured, there is every likelihood that it will absorb surrounding water if it is available. Hence, it is essential to evaluate the sorptivity of repair concrete containing CRSMs.

3. EFFECTS OF ADDITION OF DIFFERENT INGREDIENTS

Shrinkage reducing admixture (SRA) was used in one of the RSSCC mixtures adopted to study the shrinkage properties of this new material. Addition of SRA resulted in delay of the final setting time. It is recommended that a thorough analysis of RSSCC mixture containing SRA be carried out so as to have a better understanding about the effects of SRA in the presence of other chemical admixtures such as set-accelerators.

The air-void analysis of hardened repair concrete containing CRSMs revealed very low percentage of air-voids for some of the CRSMs such as Five Star Highway Patch Cement (FSHPC). Complete information about the chemical composition of this material was not available to the author. Valuable information on performance of CRSM can be acquired by carrying out a study involving addition of air entraining agent to commercial CRSMs.

In this project RSSCC was developed using high cementitious content of 560 kg/m3 which resulted in a concrete having moderate to low cracking potential. Evaluation of RSSCC using light weight aggregate can be carried out so as to reduce the cracking potential of RSSCC without the usage of shrinkage reducing admixtures. Usage of limestone powder as a part substitution for cement in RSSCC can also be evaluated.

7.4 Conclusions

This study provides criteria for long term performance of repair materials adopted for dowel bar retrofit applications. Study of four CRSMs performed during Phase-I of the research demonstrates that workability, especially the ease in placement sets the stage for the long term performance of the repair material. Currently available CRSMs require an additional amount of water to achieve ease of placing. This additional water, combined with the fact that all the CRSMs evaluated in this study contained very low percentage of air voids can lead to durability problems. The holistic approach adopted in evaluation of CRSMs in this study establishes that the durability of repair concrete is a complex issue, and that its performance is affected by workability of the repair concrete in its fresh state, temperature at the time of placement, early age development of compressive strength and bond strength, cracking susceptibility and resistance to freezing-thawing cycles.

In addition to performing assessment of available CRSMs, this thesis developed a new rapid-setting material based on the principles of self-consolidating concrete. RSSCC using small size aggregate and a ternary blend of cementitious materials was developed in the laboratory. The flowability and deformability of this material ensures a well consolidated repair patch which can increase the service life of pavements.

The mixing process, including mixing sequence, time of addition of high range water reducers (HRWR) and total mixing time affect the stability of the RSSCC mixture. This research demonstrated that for small volume mixtures containing high fine particle content, a 2-Step process of addition of polycarboxylate based HRWR improves the dispersion of cement particles leading to increased flowability. Dispersion of cement particles is also affected by the mixing action and for small volume of RSSCC batches mixing action of mortar mixers results in stable flowable RSSCC mixtures.

The robustness of RSSCC is an important issue for long term performance, especially for small volume mixtures. This work shows that deformability of RSSCC is affected by aggregate moisture content and aggregate gradation. Large deviation in slump flow and passing ability were observed due to changes in aggregate moisture content.

While this work showed that a flowable and durable RSSCC can be prepared in the laboratory, more research and experimental field installation of this material is necessary to incorporate it in to main stream repair projects.

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Appendix A- Mixture Proportions Of Phase II, Step 2, Stage 1 Mixtures

Table A-1 Mixture 1 in Phase II, Step 1

Ingredient	Quantity (kg/m^3)	Observation
Type III Cement	475	Bleeding, cement clumps, mortar halo in the slump patty and large aggregate pile in the middle of the concrete spread
Silica fume	0	
Pea gravel	563	
Sand	1017	
Water	190	
HRWR	5.1	
AEA	1.5	
Accelerator	20.87	
VMA		
Air	6.5	

Table A-2 Mixture 2 Phase II, Step 1

Ingredient	Quantity (kg/m^3)	Observation
Type III Cement	475	Mixture exhibited a slight amount of bleeding and presence of a few clumps though the amount is less than that observed in Mixture 1
Silica fume	0	
Pea gravel	581	
Sand	1029	
Water	178	
HRWR	5.1	
AEA	1.5	
Accelerator	20.87	
VMA	1.3	
Air	6.5	

Table A-3 Mixture 3 Phase II, Step 1

Ingredient	Quantity (kg/m^3)	Observation
Type III Cement	475	Some amount of air-popping.
Silica fume	0	
Pea gravel	705	
Sand	953	
Water	161	
HRWR	5.1	
AEA	0.91	
Accelerator	17.3	
VMA		
Air	6.5	

Table A-4 Mixture 4 Phase II, Step 1

Ingredient	Quantity (kg/m^3)	Observation
Type III Cement	485	Large amount of bleeding and settlement/segregation, presence of large amount of unmixed cement.
Silica fume	0	
Pea gravel	550	
Sand	1088	
Water	165	
HRWR	5.7	
AEA	1.5	
Accelerator	17.7	
VMA		
Air	6.5	

Table A-5 Mixture 5 Phase II, Step 1

Ingredient	Quantity (kg/m^3)	Observation
Type III Cement	485	Some amount of air-popping and presence of unmixed cement clumps.
Silica fume	0	
Pea gravel	595	
Sand	1046	
Water	163	
HRWR	5.7	
AEA	1.5	
Accelerator	17.7	
VMA	1.5	
Air	6.5	

Table A- 6 Mixture 6 Phase II, Step 1

Ingredient	Quantity (kg/m^3)	Observation
Cement	485	Very sticky non-cohesive mixture.
Silica fume	39	
Pea gravel	584	
Sand	1028	
Water	157	
HRWR	8.8	
AEA	1.5	
Accelerator	18.9	
VMA		
Air	6.5	

Table A- 7 Mixture 7 Phase II, Step 1

Ingredient	Quantity (kg/m^3)	Observation
Cement	485	Large amount of unmixed cement clumps and voids on the surface of cylinders of hardened concrete
Silica fume	48.5	
Pea gravel	578	
Sand	1014	
Water	160	
HRWR	9.5	
AEA		
Accelerator	20.15	
VMA		
Air	6.5	

Table A- 8 Mixture 8 Phase II, Step 1

Ingredient	Quantity (kg/m^3)	Observation
Type III Cement	485	Slight bleeding/air popping
Silica fume	48.5	
Pea gravel	578	
Sand	1014	
Water	160	
HRWR	9.5	
AEA		
Accelerator	20.15	
VMA		
Air	6.5	

Table A- 9 Mixture 9 Phase II, Step 1

Ingredient	Quantity (kg/m^3)	Observation
Type III Cement	485	Cohesive mixture
Silica fume	48.5	
Pea gravel	578	
Sand	1014	
Water	160	
HRWR	9.5	
AEA		
Accelerator	20.15	
VMA		
Air	6.5	

Table A- 10 Mixture 10 Phase II, Step 1

Ingredient	Quantity (kg/m^3)	Observation
Type III Cement	485	Slight segregation and some amount of air popping
Silica fume	48.5	
Pea gravel	578	
Sand	1014	
Water	160	
HRWR	9.5	
AEA	0.2	
Accelerator	20.15	
VMA	0.2	
Air	6.5	

Table A- 11 Mixture 11 Phase II, Step 1

Ingredient	Quantity (kg/m^3)	Observation
Type I Cement	450	Non-flowable mixture with 2 or 3 unmixed cement clumps
Silica fume	0	
Pea gravel	672	
Sand	957	
Water	180	
HRWR	4	
AEA	0.75	
Accelerator	0	
VMA	0.2	
Air	6.5	

Table A- 12 Mixture 12 Phase II, Step 1

Ingredient	Quantity (kg/m^3)	Observation
Type III Cement	450	Non-flowable mixture with 2 or 3 unmixed cement clumps
Silica fume	0	
Pea gravel	590	
Sand	1037	
Water	180	
HRWR	4.8	
AEA	0.75	
Accelerator	1.3	
VMA	0	
Air	6.5	

Table A- 13 Mixture 13 Phase II, Step 1

Ingredient	Quantity (kg/m^3)	Observation
Type I Cement	350	Mixture appeared to be gravelly and had a low slump
Silica fume	0	
Pea gravel	1003	
Sand	723	
Water	176	
HRWR	3.4	
AEA	0.75	
Accelerator	0	
VMA	0.2	
Air	6.5	

Table A- 14 Mixture 14 Phase II, Step 1

Ingredient	Quantity (kg/m^3)	Observation
Type I Cement	350	Mixture appeared to be gravelly and had a low slump
Silica fume	0	
Pea gravel	880	
Sand	830	
Water	182	
HRWR	3.6	
AEA	0.75	
Accelerator	0	
VMA	0.2	
Air	6.5	

Table A- 15 Mixture 15 Phase II, Step 1

Ingredient	Quantity (kg/m^3)	Observation
Type III Cement	450	Segregation and bleeding
Silica fume	34	
Pea gravel	728	
Sand	838	
Water	188	
HRWR	3.6	
AEA	0.75	
Accelerator	0	
VMA	0.2	
Air	6.5	

Table A- 18 Mixture 18 Phase II, Step 1

Ingredient	Quantity (kg/m^3)	Observation
Type III Cement	450	Presence of non-mixed cement clumps and segregation
Silica fume	0	
Pea gravel	927	
Sand	709	
Water	180	
HRWR	4	
AEA	0.75	
Accelerator	0	
VMA	0.2	
Air	6.5	

Table A- 19 Mixture 19 Phase II, Step 1

Ingredient	Quantity (kg/m^3)	Observation
Type III Cement	450	Presence of non-mixed cement clumps and segregation
Silica fume	0	
Pea gravel	927	
Sand	709	
Water	180	
HRWR	5.4	
AEA	0.75	
Accelerator	1.32	
VMA		
Air	6.5	

Table A 20 Mixture 20 Phase II, Step 1

Ingredient	Quantity (kg/m^3)	Observation
Type III Cement	450	Low slump
Silica fume	34	
Pea gravel	727	
Sand	840	
Water	189	
HRWR	2.3	
AEA	0.75	
Accelerator	0	
VMA	0	
Air	6.5	

Table A 21 Mixture 21 Phase II, Step 1

Ingredient	Quantity (kg/m^3)	Observation
Type III Cement	450	Cohesive mixture but cylinders of hardened concrete exhibited many voids
Silica fume	34	
Pea gravel	727	
Sand	840	
Water	189	
HRWR	5	
AEA	0.75	
Accelerator	0	
VMA	0.2	
Air	6.5	

Table A 22 Mixture 22 Phase II, Step 1

Ingredient	Quantity (kg/m^3)	Observation
Type III Cement	450	Cohesive mixture
Silica fume	34	
Pea gravel	882	
Sand	677	
Water	194	
HRWR	5	
AEA	0.75	
Accelerator	0	
VMA	0.2	
Air	6.5	

Table A 23 Mixture 23 Phase II, Step 1

Ingredient	Quantity (kg/m^3)	Observation
Type III Cement	450	Cohesive mixture
Silica fume	34	
Pea gravel	721	
Sand	832	
Water	194	
HRWR	4.4	
AEA	0.75	
Accelerator	0	
VMA	1.2	
Air	6.5	

Table A 24 Mixture 24 Phase II, Step 1

Ingredient	Quantity (kg/m^3)	Observation
Type III Cement	375	Segregation and bleeding
Silica fume	29	
Pea gravel	883	
Sand	828	
Water	162	
HRWR	2.7	
AEA	0.75	
Accelerator	0	
VMA	0	
Air	6.5	

Table A 25 Mixture 25 Phase II, Step 1

Ingredient	Quantity (kg/m^3)	Observation
Type I Cement	385	Segregation and bleeding.
Silica fume	29	
Pea gravel	700	
Sand	989	
Water	166	
HRWR	2.8	
AEA	0.75	
Accelerator	0	
VMA	1.2	
Air	6.5	

Table A 26 Mixture 26 Phase II, Step 1

Ingredient	Quantity (kg/m^3)	Observation
Type I Cement	425	Segregation and bleeding
Silica fume	32	
Pea gravel	670	
Sand	947	
Water	178	
HRWR	3.1	
AEA	0.75	
Accelerator	0	
VMA	1.2	
Air	6.5	

Table A 27 Mixture 27 Phase II, Step 1

Ingredient	Quantity (kg/m^3)	Observation
Type I Cement	500	Segregation and slight bleeding
Silica fume	0	
Pea gravel	800	
Sand	797	
Water	185	
HRWR	4.9	
AEA	0.75	
Accelerator	0	
VMA	0.9	
Air	6.5	

Table A 28 Mixture 28 Phase II, Step 1

Ingredient	Quantity (kg/m^3)	Observation
Type I Cement	500	Slight settling of aggregates
Silica fume	0	
Pea gravel	722	
Sand	853	
Water	185	
HRWR	4.9	
AEA	0.75	
Accelerator	0	
VMA	0.9	
Air	6.5	

Appendix B- Visual Stability Index

Figure B-1 Slump flow indicating VSI 0.

Figure B-2 Slump flow indicating VSI-2.

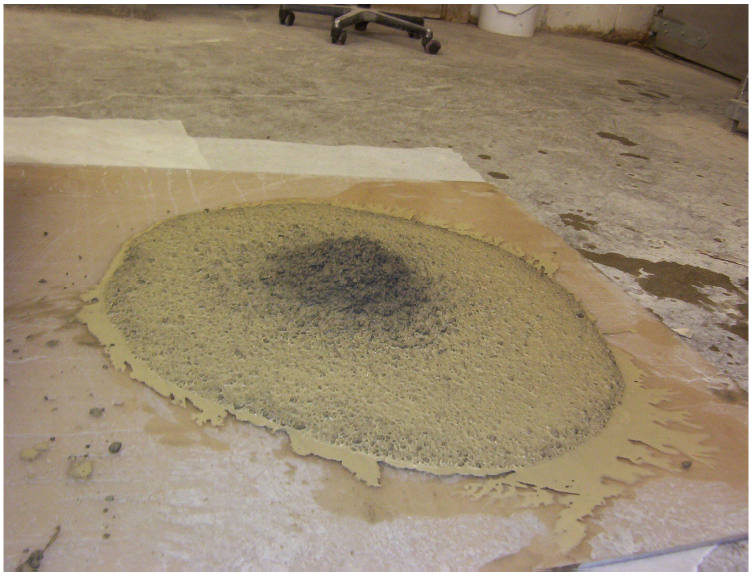


Figure B-3 Slump flow indicating VSI-3.

Appendix C- Mixture Proportions Of Phase Ii, Step 2, Stage 2 Mixtures

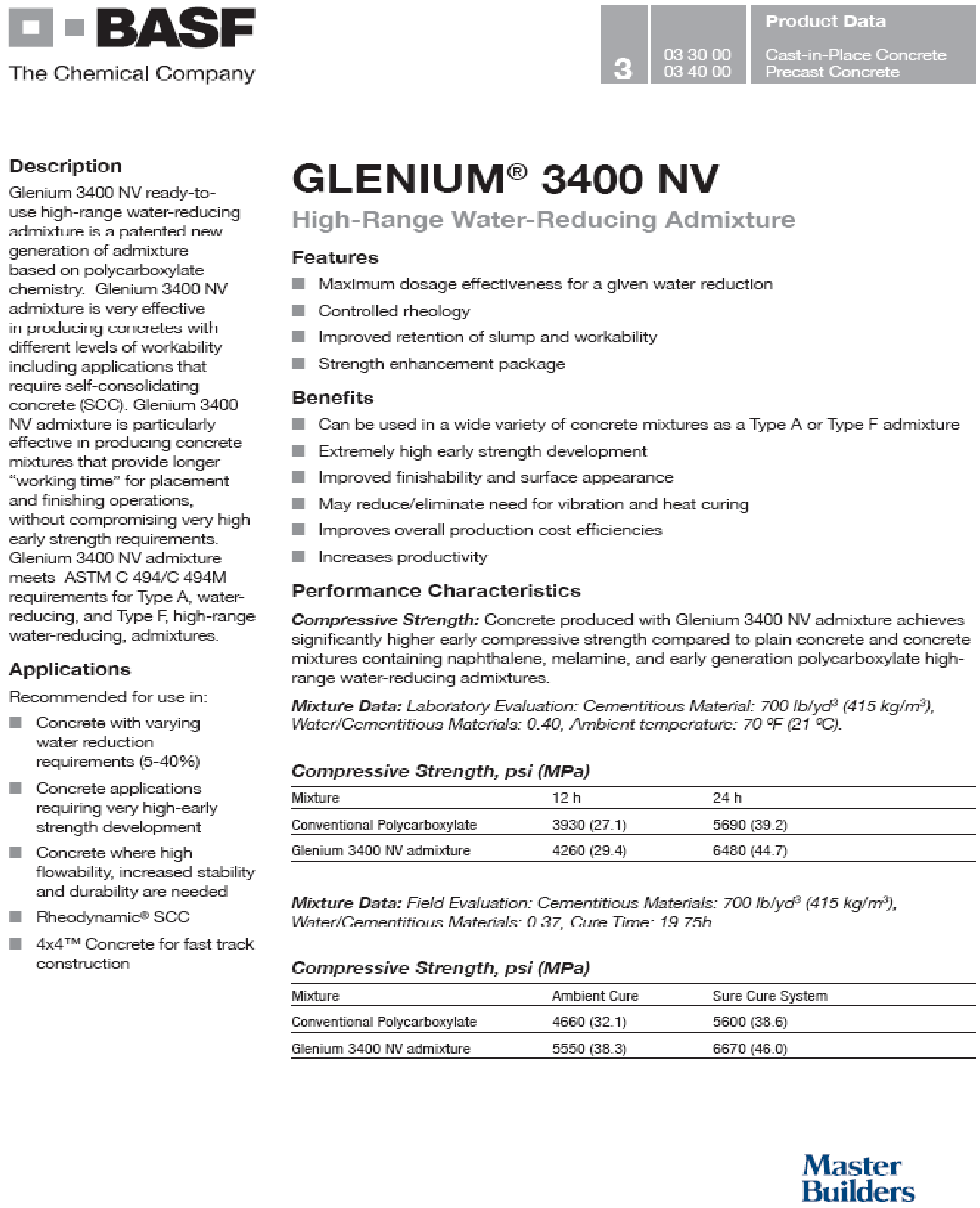
Table C1 Mixture 1 Phase II, Step 1, Stage 2

Ingredient	Quantity (kg/m^3)	Observation and Test Result
Cement	500	Air-popping observed in the slump flow patty, slump flow- 635 mm, Compressive strength at end of 6h- 14 MPa
Silica fume	10	
Pea gravel	589	
Sand	1055	
Water	171	
HRWR	5.9	
AEA	0.75	
Accelerator	19.5	
VMA	0.9	
Air	6.5	

Table C2 Mixture 2 Phase II, Step 1, Stage 2

Ingredient	Quantity (kg/m^3)	Observation and Test Result
Cement	490	Air-popping observed in the slump flow patty, slump flow- 635 mm, Compressive strength at end of 6h- 13 MPa
Silica fume	5	
Pea gravel	597	
Sand	1069	
Water	171	
HRWR	5.9	
AEA	0.75	
Accelerator	19.5	
VMA	0.9	
Air	6.5	

Appendix D1- Glenium® 3400 NV



BASF
The Chemical Company

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03 30 00
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Product Data
Cast-in-Place Concrete
Precast Concrete

GLENIUM® 3400 NV

High-Range Water-Reducing Admixture

Description

Glenium 3400 NV ready-to-use high-range water-reducing admixture is a patented new generation of admixture based on polycarboxylate chemistry. Glenium 3400 NV admixture is very effective in producing concretes with different levels of workability including applications that require self-consolidating concrete (SCC). Glenium 3400 NV admixture is particularly effective in producing concrete mixtures that provide longer "working time" for placement and finishing operations, without compromising very high early strength requirements. Glenium 3400 NV admixture meets ASTM C 494/C 494M requirements for Type A, water-reducing, and Type F, high-range water-reducing, admixtures.

Applications

Recommended for use in:

- Concrete with varying water reduction requirements (5-40%)
- Concrete applications requiring very high-early strength development
- Concrete where high flowability, increased stability and durability are needed
- Rheodynamic® SCC
- 4x4™ Concrete for fast track construction

Features

- Maximum dosage effectiveness for a given water reduction
- Controlled rheology
- Improved retention of slump and workability
- Strength enhancement package

Benefits

- Can be used in a wide variety of concrete mixtures as a Type A or Type F admixture
- Extremely high early strength development
- Improved finishability and surface appearance
- May reduce/eliminate need for vibration and heat curing
- Improves overall production cost efficiencies
- Increases productivity

Performance Characteristics

Compressive Strength: Concrete produced with Glenium 3400 NV admixture achieves significantly higher early compressive strength compared to plain concrete and concrete mixtures containing naphthalene, melamine, and early generation polycarboxylate high-range water-reducing admixtures.

Mixture Data: *Laboratory Evaluation: Cementitious Material: 700 lb/yd^3 (415 kg/m^3), Water/Cementitious Materials: 0.40, Ambient temperature: 70 °F (21 °C).*

Compressive Strength, psi (MPa)

Mixture	12 h	24 h
Conventional Polycarboxylate	3930 (27.1)	5690 (39.2)
Glenium 3400 NV admixture	4260 (29.4)	6480 (44.7)

Mixture Data: *Field Evaluation: Cementitious Materials: 700 lb/yd^3 (415 kg/m^3), Water/Cementitious Materials: 0.37, Cure Time: 19.75h.*

Compressive Strength, psi (MPa)

Mixture	Ambient Cure	Sure Cure System
Conventional Polycarboxylate	4660 (32.1)	5600 (38.6)
Glenium 3400 NV admixture	5550 (38.3)	6670 (46.0)

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Product Data: GLENIUM® 3400 NV

Slump Retention: Glenium 3400 NV admixture was developed to provide extremely high-early strength concrete that exhibits good slump and workability retention characteristics, relative to other high-early strength-producing high-range water-reducing admixtures. A field trial mixture is recommended to ensure that the desired slump at a specific time period is achieved.

Guidelines for Use

Dosage: Glenium 3400 NV admixture has a recommended dosage range of 2-12 fl oz/cwt (130-780 mL/100 kg) of cementitious materials. For most applications, dosages in the range of 2-6 fl oz/cwt (130-360 mL/100 kg) will provide excellent performance. For very high performance and Rheodynamic Self-Consolidating Concrete mixtures, up to 12 fl oz/cwt (780 mL/100 kg) of cementitious materials can be utilized. Because of variations in concrete materials, job site conditions and/or applications, dosages outside of the recommended range may be required. In such cases, contact your local BASF Admixtures, Inc. representative.

Mixing: Glenium 3400 NV admixture can be added with the initial batch water or as a delayed addition. However, optimum water reduction is generally obtained with a delayed addition.

Product Notes

Corrosivity – Non-Chloride, Non-Corrosive: Glenium 3400 NV admixture will neither initiate nor promote corrosion of reinforcing steel embedded in concrete, prestressing steel or of galvanized steel floor and roof systems. Neither calcium chloride nor other chloride-based ingredients are used in the manufacture of Glenium 3400 NV admixture.

Compatibility: Glenium 3400 NV admixture is compatible with most admixtures used in the production of quality concrete, including normal, mid-range and high-range water-reducing admixtures, air-entrainers, accelerators, retarders, extended set control admixtures, corrosion inhibitors, and shrinkage reducers.

Do not use Glenium 3400 NV admixture with admixtures containing beta-naphthalene sulfonate. Erratic behaviors in slump, workability retention and pumpability may be experienced.

Storage and Handling

Storage Temperature: Glenium 3400 NV admixture must be stored at temperatures above 40 °F (5 °C). If Glenium 3400 NV admixture freezes, it can be thawed by warming and reconstituted by mechanical agitation. ***Do not use pressurized air for agitation.***

Shelf Life: Glenium 3400 NV admixture has a minimum shelf life of 6 months. Depending on storage conditions, the shelf life may be greater than stated. To ensure the longest shelf life potential, recirculation is recommended. Please contact your BASF Admixtures, Inc. representative regarding suitability for use and dosage recommendations if the shelf life of Glenium 3400 NV admixture has been exceeded.

Packaging

Glenium 3400 NV admixture is supplied in 55 gal (208 L) drums, 275 gal (1040 L) totes and by bulk delivery.

Related Documents

Material Safety Data Sheets: Glenium 3400 NV admixture.

Additional Information

For additional information on Glenium 3400 NV admixture or its use in developing concrete mixtures with special performance characteristics, contact your BASF Admixtures, Inc. representative.

BASF Admixtures, Inc. is a leading provider of innovative chemical admixtures and silica fume for specialty concrete used in the ready mix, precast, manufactured concrete products, underground construction and paving markets in the United States and Canada. The Company's respected Master Builders brand products are used to improve the placing, pumping, finishing, appearance and performance characteristics of concrete.

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Canada 1800 Clark Boulevard, Brampton, Ontario L6T 4M7 ■ Tel: 800 387-5862 ■ Fax: 905 792-0651

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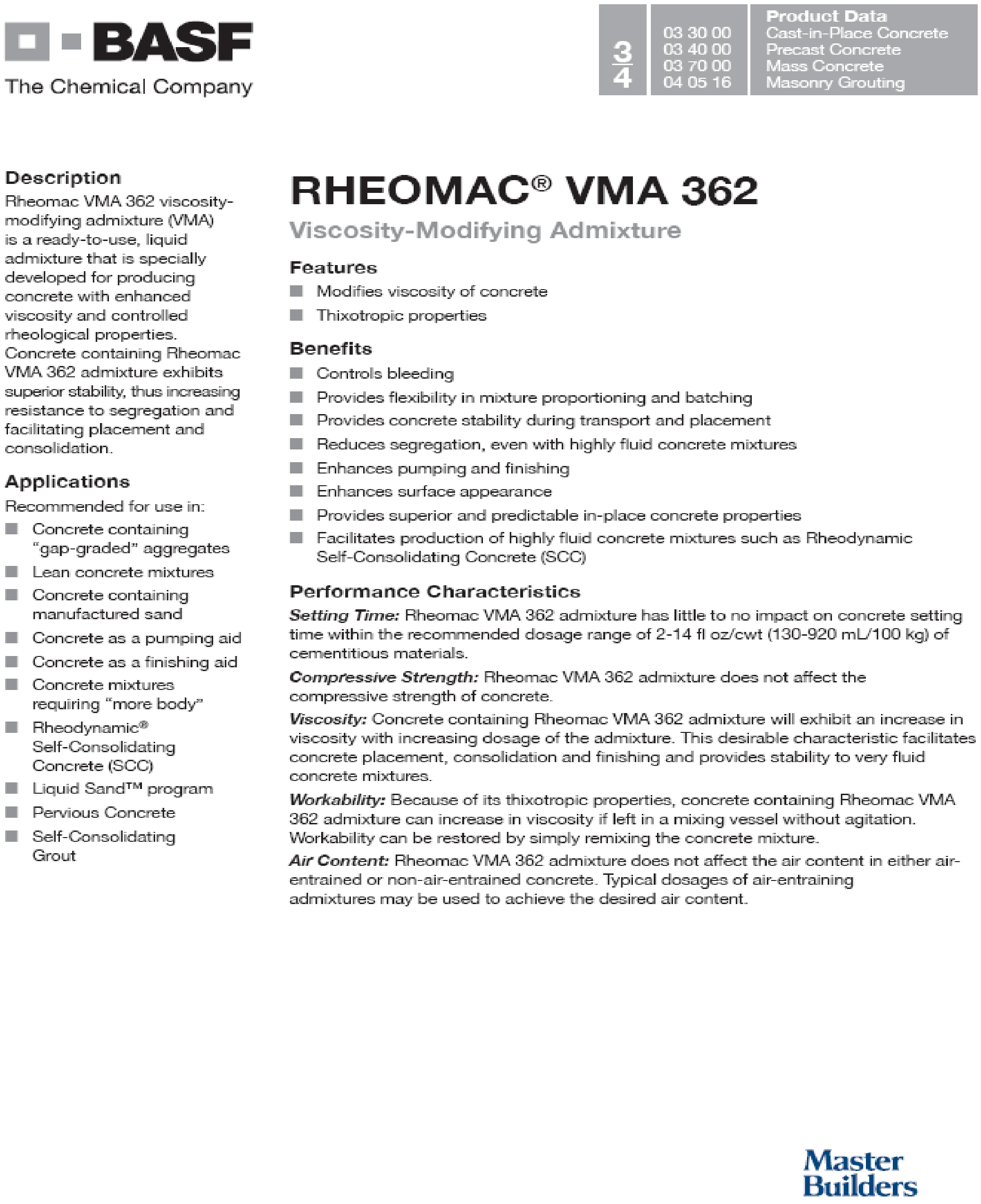
Appendix D2- Rheomac® VMA 362



BASF
The Chemical Company

3 4		Product Data
	03 30 00	Cast-in-Place Concrete
	03 40 00	Precast Concrete
	03 70 00	Mass Concrete
	04 05 16	Masonry Grouting

RHEOMAC® VMA 362

Viscosity-Modifying Admixture

Description

Rheomac VMA 362 viscosity-modifying admixture (VMA) is a ready-to-use, liquid admixture that is specially developed for producing concrete with enhanced viscosity and controlled rheological properties. Concrete containing Rheomac VMA 362 admixture exhibits superior stability, thus increasing resistance to segregation and facilitating placement and consolidation.

Applications

Recommended for use in:

- Concrete containing "gap-graded" aggregates
- Lean concrete mixtures
- Concrete containing manufactured sand
- Concrete as a pumping aid
- Concrete as a finishing aid
- Concrete mixtures requiring "more body"
- Rheodynamic® Self-Consolidating Concrete (SCC)
- Liquid Sand™ program
- Pervious Concrete
- Self-Consolidating Grout

Features

- Modifies viscosity of concrete
- Thixotropic properties

Benefits

- Controls bleeding
- Provides flexibility in mixture proportioning and batching
- Provides concrete stability during transport and placement
- Reduces segregation, even with highly fluid concrete mixtures
- Enhances pumping and finishing
- Enhances surface appearance
- Provides superior and predictable in-place concrete properties
- Facilitates production of highly fluid concrete mixtures such as Rheodynamic Self-Consolidating Concrete (SCC)

Performance Characteristics

Setting Time: Rheomac VMA 362 admixture has little to no impact on concrete setting time within the recommended dosage range of 2-14 fl oz/cwt (130-920 mL/100 kg) of cementitious materials.

Compressive Strength: Rheomac VMA 362 admixture does not affect the compressive strength of concrete.

Viscosity: Concrete containing Rheomac VMA 362 admixture will exhibit an increase in viscosity with increasing dosage of the admixture. This desirable characteristic facilitates concrete placement, consolidation and finishing and provides stability to very fluid concrete mixtures.

Workability: Because of its thixotropic properties, concrete containing Rheomac VMA 362 admixture can increase in viscosity if left in a mixing vessel without agitation. Workability can be restored by simply remixing the concrete mixture.

Air Content: Rheomac VMA 362 admixture does not affect the air content in either air-entrained or non-air-entrained concrete. Typical dosages of air-entraining admixtures may be used to achieve the desired air content.

Master Builders

Product Data: RHEOMAC® VMA 362

Guidelines for Use

Dosage: The recommended dosage range for Rheomac VMA 362 admixture is 2-14 fl oz/cwt (130-910 mL/100 kg) of cementitious materials. A dosage of 2-6 fl oz/cwt (130-390 mL/100 kg) is recommended for typical concrete mixtures requiring "more body" to facilitate pumping and finishing procedures. A dosage of up to 14 fl oz/cwt (910 mL/100 kg) is recommended to provide stability in self-consolidating concrete mixtures. Because of variations in concrete materials, job site conditions and/or applications, dosages outside of the suggested range may be required.

Mixing: Rheomac VMA 362 admixture is typically added with the initial mix water. Alternately, Rheomac VMA 362 admixture may be added after all other concreting ingredients have been batched and thoroughly mixed, either at the batch plant or at the jobsite.

Product Notes

Compatibility: Rheomac VMA 362 admixture is compatible with most admixtures used in the production of quality concrete including normal, mid-range and high-range water-reducing admixtures and air entrainers. Rheomac VMA 362 admixture is also compatible with typical accelerators, retarders, extended set-control admixtures, corrosion inhibitors, and shrinkage reducers. However, a field trial mixture is recommended to ensure appropriate performance.

Storage and Handling

Storage Temperature: Rheomac VMA 362 admixture must be stored at temperatures above 32 °F (0 °C) and below 130 °F (54 °C). Protect Rheomac VMA 362 admixture from freezing because it cannot be reconstituted after thawing.

Shelf Life: A product stability evaluation has shown that Rheomac VMA 362 admixture has a shelf life of 8 months. Please contact your BASF Admixtures, Inc. representative regarding suitability for use and dosage recommendations if the stated minimum shelf life of Rheomac VMA 362 admixture has been exceeded.

Dispensing: Rheomac VMA 362 admixture should be dispensed using direct-feed dispensing systems. It is recommended that fail-safe features must be included in this dispenser application for potential meter malfunctions. Consult your local BASF Admixtures, Inc. sales representative for the proper dispensing equipment for Rheomac VMA 362 admixture.

Packaging

Rheomac VMA 362 admixture is supplied in 55 gal (208 L) drums, 275 gal (1040 L) totes, and by bulk delivery.

Related Documents

Material Safety Data Sheets: Rheomac VMA 362 admixture.

Additional Information

For additional information on Rheomac VMA 362 admixture or its use in developing concrete mixtures with special performance characteristics, contact your BASF Admixtures, Inc. representative.

BASF Admixtures, Inc. is a leading provider of innovative chemical admixtures and silica fume for specialty concrete used in the ready mix, precast, manufactured concrete products, underground construction and paving markets in the United States and Canada. The Company's respected Master Builders brand products are used to improve the placing, pumping, finishing, appearance and performance characteristics of concrete.

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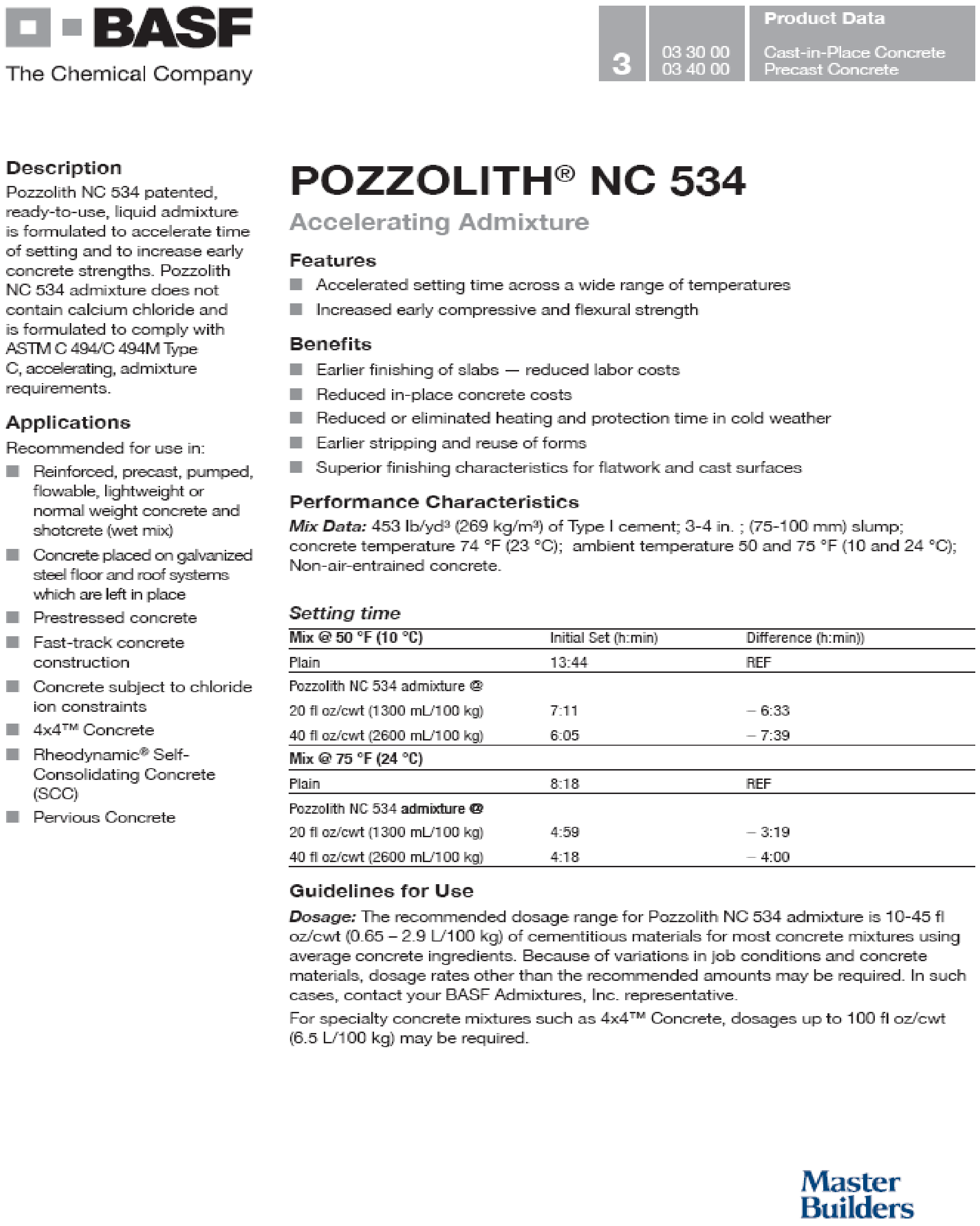
Appendix D3- Pozzolith® NC 534



BASF
The Chemical Company

3 | 03 30 00
03 40 00 | **Product Data**
Cast-in-Place Concrete
Precast Concrete

POZZOLITH® NC 534

Accelerating Admixture

Description

Pozzolith NC 534 patented, ready-to-use, liquid admixture is formulated to accelerate time of setting and to increase early concrete strengths. Pozzolith NC 534 admixture does not contain calcium chloride and is formulated to comply with ASTM C 494/C 494M Type C, accelerating, admixture requirements.

Applications

Recommended for use in:

- Reinforced, precast, pumped, flowable, lightweight or normal weight concrete and shotcrete (wet mix)
- Concrete placed on galvanized steel floor and roof systems which are left in place
- Prestressed concrete
- Fast-track concrete construction
- Concrete subject to chloride ion constraints
- 4x4™ Concrete
- Rheodynamic® Self-Consolidating Concrete (SCC)
- Pervious Concrete

Features

- Accelerated setting time across a wide range of temperatures
- Increased early compressive and flexural strength

Benefits

- Earlier finishing of slabs — reduced labor costs
- Reduced in-place concrete costs
- Reduced or eliminated heating and protection time in cold weather
- Earlier stripping and reuse of forms
- Superior finishing characteristics for flatwork and cast surfaces

Performance Characteristics

Mix Data: 453 lb/yd³ (269 kg/m³) of Type I cement; 3-4 in. ; (75-100 mm) slump; concrete temperature 74 °F (23 °C); ambient temperature 50 and 75 °F (10 and 24 °C); Non-air-entrained concrete.

Setting time

Mix @ 50 °F (10 °C)	Initial Set (h:min)	Difference (h:min))
Plain	13:44	REF
Pozzolith NC 534 admixture @		
20 fl oz/cwt (1300 mL/100 kg)	7:11	– 6:33
40 fl oz/cwt (2600 mL/100 kg)	6:05	– 7:39
Mix @ 75 °F (24 °C)		
Plain	8:18	REF
Pozzolith NC 534 **admixture @**		
20 fl oz/cwt (1300 mL/100 kg)	4:59	– 3:19
40 fl oz/cwt (2600 mL/100 kg)	4:18	– 4:00

Guidelines for Use

Dosage: The recommended dosage range for Pozzolith NC 534 admixture is 10-45 fl oz/cwt (0.65 – 2.9 L/100 kg) of cementitious materials for most concrete mixtures using average concrete ingredients. Because of variations in job conditions and concrete materials, dosage rates other than the recommended amounts may be required. In such cases, contact your BASF Admixtures, Inc. representative.

For specialty concrete mixtures such as 4x4™ Concrete, dosages up to 100 fl oz/cwt (6.5 L/100 kg) may be required.

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Product Data: POZZOLITH® NC 534

Product Notes

Corrosivity – Non-Chloride, Non-Corrosive: Pozzolith NC 534 admixture will neither initiate nor promote corrosion of reinforcing steel in concrete.

Compatibility: Pozzolith NC 534 admixture may be used in combination with any BASF Admixtures, Inc. admixture. When used in conjunction with other admixtures, each admixture must be dispensed separately into the mix.

Storage and Handling

Storage Temperature: Store at 5 °F (-15 °C) or above. If Pozzolith NC 534 admixture freezes, thaw at 35 °F (2 °C) or above and completely reconstitute by mild mechanical agitation. ***Do not use pressurized air for agitation.***

Shelf Life: Pozzolith NC 534 admixture has a minimum shelf life of 18 months. Depending on storage conditions, the shelf life may be greater than stated. Please contact your BASF Admixtures, Inc. representative regarding suitability for use and dosage recommendations if the shelf life of Pozzolith NC 534 admixture has been exceeded.

Packaging

This product is supplied in 55 gal (208 L) drums, 275 gal (1040 L) totes and by bulk delivery.

Related Documents

Material Safety Data Sheets: Pozzolith NC 534 admixture.

Additional Information

For additional information on Pozzolith NC 534 admixture or its use in developing a concrete mixture with special performance characteristics, contact your BASF Admixtures, Inc. representative.

BASF Admixtures, Inc. is a leading provider of innovative chemical admixtures and silica fume for specialty concrete used in the ready mix, precast, manufactured concrete products, underground construction and paving markets in the United States and Canada. The Company's respected Master Builders brand products are used to improve the placing, pumping, finishing, appearance and performance characteristics of concrete.

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Appendix D4- SET® 45 and SET® 45 HW

degussa.
Construction Chemicals

SET® 45 AND SET® 45 HW

Chemical-action repair mortar

PRODUCT DATA

3 03930 **Concrete Rehabilitation**

Description

Set® 45 is a one-component magnesium phosphate-based patching and repair mortar. This concrete repair and anchoring material sets in approximately 15 minutes and takes rubber-tire traffic in 45 minutes. It comes in two formulations: Set® 45 Regular for ambient temperatures below 85° F (29° C) and Set® 45 Hot Weather for ambient temperatures ranging from 85 to 100° F (29 to 38° C).

Yield

A 50 lb (22.7 kg) bag of mixed with the required amount of water produces a volume of approximately 0.39 ft³ (0.011 m³); 60% extension using 1/2" (13 mm) rounded, sound aggregate produces approximately 0.58 ft³ (0.016 m³).

Packaging

50 lb (22.7 kg) multi-wall bags

Color

Dries to a natural gray color

Shelf Life

1 year when properly stored

Storage

Store in unopened containers in a clean, dry area between 45 and 90° F (7 and 32° C).

Features	Benefits
• Single component	Just add water and mix
• Reaches 2,000 psi compressive strength in 1 hour	Rapidly returns repairs to service
• Wide temperature use range	From below freezing to hot weather exposures
• Superior bonding	Bonds to concrete and masonry without a bonding agent
• Very low drying shrinkage	Improved bond to surrounding concrete
• Resistant to freeze/thaw cycles and deicing chemicals	Usable in most environments
• Only air curing required	Fast, simple curing process
• Thermal expansion and contraction similar to Portland cement concrete	More permanent repairs
• Sulfate resistant	Stable where conventional mortars degrade

Where to Use

APPLICATION

- Heavy industrial repairs
- Dowel bar replacement
- Concrete pavement joint repairs
- Full-depth structural repairs
- Setting of expansion device nosings
- Bridge deck and highway overlays
- Anchoring iron or steel bridge and balcony railings
- Commercial freezer rooms
- Truck docks
- Parking decks and ramps
- Airport runway-light installations

LOCATION

- Horizontal and formed vertical or overhead surfaces
- Indoor and outdoor applications

How to Apply

Surface Preparation

1. A sound substrate is essential for good repairs. Flush the area with clean water to remove all dust.
2. Any surface carbonation in the repair area will inhibit chemical bonding. Apply a pH indicator to the prepared surface to test for carbonation.
3. Air blast with oil-free compressed air to remove all water before placing Set® 45.

Mixing

1. Set® 45 must be mixed, placed, and finished within 10 minutes in normal temperatures (72° F [22° C]). Only mix quantities that can be placed in 10 minutes or less.
2. Do not deviate from the following sequence; it is important for reducing mixing time and producing a consistent mix. Use a minimum 1/2" slow-speed drill and mixing paddle or an appropriately sized mortar mixer. Do not mix by hand.
3. Pour clean (potable) water into mixer. Water content is critical. Use a maximum of 4 pts (1.9 L) of water per 50 lb (22.7 kg) bag of Set® 45. Do not deviate from the recommended water content.

Technical Data

Composition

Set® 45 is a magnesium-phosphate patching and repair mortar.

Test Data

PROPERTY	RESULTS	TEST METHODS
Typical Compressive Strengths*, psi (MPa)		ASTM C 109, modified

	Plain Concrete 72° F (22° C)	Set® 45 Regular 72° F (22° C)	Set® 45 Regular 36° F (2° C)	Set® 45 HW 95° F (35° C)
1 hour	—	2,000 (13.8)	—	—
3 hour	—	5,000 (34.5)	—	3,000 (20.7)
6 hour	—	5,000 (34.5)	1,200 (8.3)	5,000 (34.5)
1 day	500 (3.5)	6,000 (41.4)	5,000 (34.5)	6,000 (41.4)
3 day	1,900 (13.1)	7,000 (48.3)	7,000 (48.3)	7,000 (48.3)
28 day	4,000 (27.6)	8,500 (58.6)	8,500 (58.6)	8,500 (55.2)

NOTE: Only Set® 45 Regular formula, tested at 72° F (22° C), obtains 2,000 psi (13.8 MPa) compressive strength in 1 hour.

Modulus of Elasticity, psi (MPa)	7 days	28 days	ASTM C 469
Set® 45 Regular	4.18×10^6 (2.88×10^4)	4.55×10^6 (3.14×10^4)	
Set® 45 Hot Weather	4.90×10^6 (3.38×10^4)	5.25×10^6 (3.62×10^4)	

PROPERTY	RESULTS	TEST METHODS
Freeze/thaw durability test, % RDM, 300 cycles, for Set® 45 and Set 45® HW	80	ASTM C 666, Procedure A (modified**)
Scaling resistance to deicing chemicals, Set® 45 and Set 45® HW		ASTM C 672
5 cycles	0	
25 cycles	0	
50 cycles	1.5 (slight scaling)	
Sulfate resistance		ASTM C 1012
Set® 45 length change after 52 weeks, %	0.09	
Type V cement mortar after 52 weeks, %	0.20	
Typical setting times, min, for Set® 45 at 72° F (22° C), and Set® 45 Hot Weather at 95° F (35° C)		Gilmore ASTM C 266, modified
Initial set	9 – 15	
Final set	10 – 20	
Coefficient of thermal expansion,*** both Set® 45 Regular and Set® 45 Hot Weather coefficients	7.15×10^{-6}/° F (12.8×10^{-6}/° C)	CRD-C 39
Flexural Strength, psi (MPa), 3 by 4 by 16" (75 by 100 by 406 mm) prisms, 1 day strength,		ASTM C 78, modified
Set® 45 mortar	550 (3.8)	
Set® 45 mortar with 3/8" (9 mm) pea gravel	600 (4.2)	
Set® 45 mortar with 3/8" (9 mm) crushed angular noncalcareous hard aggregate	650 (4.5)	

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* All tests were performed with neat material (no aggregate)

**Method discontinues test when 300 cycles or an RDM of 60% is reached.

***Determined using 1 by 1 by 11" (25 mm by 25 mm by 279 mm) bars. Test was run with neat mixes (no aggregate). Extended mixes (with aggregate) produce lower coefficients of thermal expansion.

Test results are averages obtained under laboratory conditions. Expect reasonable variations.

4. Add the powder to the water and mix for approximately 1 – 1-1/2 minutes.

5. Use neat material for patches from 1/2 – 2" (6 – 51 mm) in depth or width. For deeper patches, extend a 50 lb (22.7 kg) bag of Set® 45 HW by adding up to 30 lbs (13.6 kg) of properly graded, dust-free, hard, rounded aggregate or noncalcareous crushed angular aggregate, not exceeding 1/2" (6 mm) in accordance with ASTM C 33, #8. If aggregate is damp, reduce water content accordingly. Special procedures must be followed when angular aggregate is used. Contact your local Degussa representative for more information. (Do not use calcareous aggregate made from soft limestone. Test aggregate for fizzing with 10% HCL).

Application

1. Immediately place the mixture onto the properly prepared substrate. Work the material firmly into the bottom and sides of the patch to ensure good bond.

2. Level the Set® 45 and screed to the elevation of the existing concrete. Minimal finishing is required. Match the existing concrete texture.

Curing

No curing is required, but protect from rain immediately after placing. Liquid-membrane curing compounds or plastic sheeting may be used to protect the early surface from precipitation, but never wet cure Set® 45.

For Best Performance

- Color variations are not indicators of abnormal product performance.
- Regular Set® 45 will not freeze at temperatures above -20° F (-29° C) when appropriate precautions are taken.
- Do not add sand, fine aggregate, or Portland cement to Set® 45.
- Do not use Set® 45 for patches less than 1/2" (13 mm) deep. For deep patches, use Set® 45 Hot Weather formula extended with aggregate, regardless of the temperature. Consult your Degussa representative for further instructions.
- Do not use limestone aggregate.
- Water content is critical. Do not deviate from the recommended water content printed on the bag.
- Precondition these materials to approximately 70° F (21° C) for 24 hours before using.
- Protect repairs from direct sunlight, wind, and other conditions that could cause rapid drying of material.
- When mixing or placing Set® 45 in a closed area, provide adequate ventilation.
- Do not use Set® 45 as a precision nonshrink grout.
- Never featheredge Set® 45; for best results, always sawcut the edges of a patch.
- Prevent any moisture loss during the first 3 hours after placement. Protect Set® 45 with plastic sheeting or a curing compound in rapid-evaporation conditions.
- Do not wet cure.
- Do not place Set® 45 on a hot (90° F [32° C]), dry substrate.
- When using Set® 45 in contact with galvanized steel or aluminum, consult your local Degussa sales representative.
- Make certain the most current versions of product data sheet and MSDS are being used; call Customer Service (1-800-433-9517) to verify the most current versions.
- Proper application is the responsibility of the user. Field visits by Degussa personnel are for the purpose of making technical recommendations only and not for supervising or providing quality control on the jobsite.

Health and Safety

SET® 45

Caution

Risks

Eye irritant. Skin irritant. Lung irritant. May cause delayed lung injury.

Precautions

KEEP OUT OF THE REACH OF CHILDREN. Avoid contact with eyes. Wear suitable protective eyewear. Avoid prolonged or repeated contact with skin. Wear suitable gloves. Wear suitable protective clothing. Do not breathe dust. In case of insufficient ventilation, wear suitable respiratory equipment. Wash soiled clothing before reuse.

First Aid

Wash exposed skin with soap and water. Flush eyes with large quantities of water. If breathing is difficult, move person to fresh air.

Waste Disposal Method

This product when discarded or disposed of is not listed as a hazardous waste in federal regulations. Dispose of in a landfill in accordance with local regulations.

For additional information on personal protective equipment, first aid, and emergency procedures, refer to the product Material Safety Data Sheet (MSDS) on the job site or contact the company at the address or phone numbers given below.

Proposition 65

This product contains materials listed by the state of California as known to cause cancer, birth defects, or reproductive harm.

VOC Content

0 lbs/gal or 0 g/L.

For medical emergencies only, call ChemTrec (1-800-424-9300).

Degussa Building Systems

889 Valley Park Drive
Shakopee, MN, 55379

www.degussabuildingsystems.com

Customer Service 800-433-9517
Technical Service 800-243-6739

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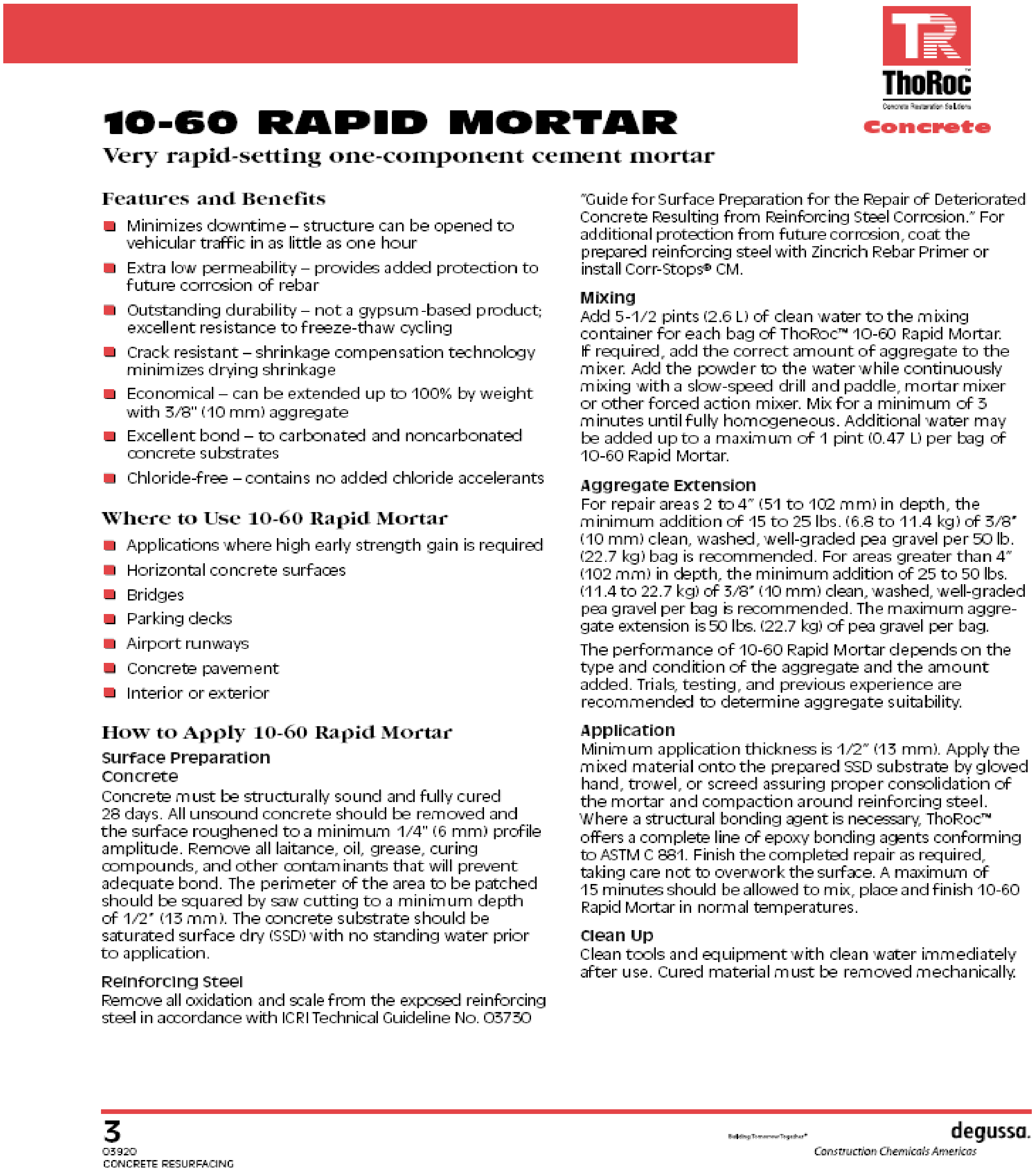
Appendix D5- ThoRoc™ 10-60 Rapid Mortar



ThoRoc™
Concrete Restoration Solutions
Concrete

10-60 RAPID MORTAR

Very rapid-setting one-component cement mortar

Features and Benefits

- Minimizes downtime – structure can be opened to vehicular traffic in as little as one hour
- Extra low permeability – provides added protection to future corrosion of rebar
- Outstanding durability – not a gypsum-based product; excellent resistance to freeze-thaw cycling
- Crack resistant – shrinkage compensation technology minimizes drying shrinkage
- Economical – can be extended up to 100% by weight with 3/8" (10 mm) aggregate
- Excellent bond – to carbonated and noncarbonated concrete substrates
- Chloride-free – contains no added chloride accelerants

Where to Use 10-60 Rapid Mortar

- Applications where high early strength gain is required
- Horizontal concrete surfaces
- Bridges
- Parking decks
- Airport runways
- Concrete pavement
- Interior or exterior

How to Apply 10-60 Rapid Mortar

Surface Preparation

Concrete

Concrete must be structurally sound and fully cured 28 days. All unsound concrete should be removed and the surface roughened to a minimum 1/4" (6 mm) profile amplitude. Remove all laitance, oil, grease, curing compounds, and other contaminants that will prevent adequate bond. The perimeter of the area to be patched should be squared by saw cutting to a minimum depth of 1/2" (13 mm). The concrete substrate should be saturated surface dry (SSD) with no standing water prior to application.

Reinforcing Steel

Remove all oxidation and scale from the exposed reinforcing steel in accordance with ICRI Technical Guideline No. 03730 "Guide for Surface Preparation for the Repair of Deteriorated Concrete Resulting from Reinforcing Steel Corrosion." For additional protection from future corrosion, coat the prepared reinforcing steel with Zincrich Rebar Primer or install Corr-Stops® CM.

Mixing

Add 5-1/2 pints (2.6 L) of clean water to the mixing container for each bag of ThoRoc™ 10-60 Rapid Mortar. If required, add the correct amount of aggregate to the mixer. Add the powder to the water while continuously mixing with a slow-speed drill and paddle, mortar mixer or other forced action mixer. Mix for a minimum of 3 minutes until fully homogeneous. Additional water may be added up to a maximum of 1 pint (0.47 L) per bag of 10-60 Rapid Mortar.

Aggregate Extension

For repair areas 2 to 4" (51 to 102 mm) in depth, the minimum addition of 15 to 25 lbs. (6.8 to 11.4 kg) of 3/8" (10 mm) clean, washed, well-graded pea gravel per 50 lb. (22.7 kg) bag is recommended. For areas greater than 4" (102 mm) in depth, the minimum addition of 25 to 50 lbs. (11.4 to 22.7 kg) of 3/8" (10 mm) clean, washed, well-graded pea gravel per bag is recommended. The maximum aggregate extension is 50 lbs. (22.7 kg) of pea gravel per bag.

The performance of 10-60 Rapid Mortar depends on the type and condition of the aggregate and the amount added. Trials, testing, and previous experience are recommended to determine aggregate suitability.

Application

Minimum application thickness is 1/2" (13 mm). Apply the mixed material onto the prepared SSD substrate by gloved hand, trowel, or screed assuring proper consolidation of the mortar and compaction around reinforcing steel. Where a structural bonding agent is necessary, ThoRoc™ offers a complete line of epoxy bonding agents conforming to ASTM C 881. Finish the completed repair as required, taking care not to overwork the surface. A maximum of 15 minutes should be allowed to mix, place and finish 10-60 Rapid Mortar in normal temperatures.

Clean Up

Clean tools and equipment with clean water immediately after use. Cured material must be removed mechanically.

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Curing

Proper curing is extremely important. 10-60 Rapid Mortar should be cured immediately after finishing. A water-based curing compound which complies with ASTM C 309 is recommended. Alternative curing options include application of a fine mist of water, wet burlap, or polyethylene sheeting for a minimum of 2 days.

For Best Performance

- Minimum ambient, surface and material temperature is 40°F (4°C) and rising.
- Do not mix longer than 5 minutes.
- Minimum application thickness is 1/2" (13 mm).
- Do not mix more material than can be used in 8 - 10 minutes at 72°F (22°C).
- Consult coating supplier for overcoating requirements.
- Make certain the most current version of this data guide is being used; call Customer Service (1-800-433-9517) to verify the most current version.
- Proper application is the responsibility of the user. Field visits by ChemRex® personnel are for the purpose of making technical recommendations only and are not for supervising or providing quality control on the jobsite.

Technical Data

Physical Properties

The following results were obtained with a water/powder ratio of 5.5 pints (2.6 L) of water to 50 lb. (22.7 kg) of 10-60 Rapid Mortar at 73°F (23°C).

Compliances

- ASTM C 928

Description of Test	Test Method	Typical Result
Fresh wet density	ASTM C 138	130 lb./ft.^{3} (2,082 kg/m^3)
Set time @ 72°F (22°C)	ASTM C 191	
Initial		16 minutes
Final		28 minutes
Working time		8 minutes
Length change	ASTM C 928	
Drying shrinkage		-0.02% (-200 µstrain)
Wetting expansion		+0.01% (+100 µstrain)
Coefficient of thermal expansion	CRD C 39	7.0 x 10^{-6} in/in/°F (12.6 x 10^{-6} cm/cm/°C)
Modulus of elasticity	ASTM C 469	4.4 x 10^{6} psi (19.5 GPa)
Rapid chloride permeability	ASTM C 1202	less than 300 coulombs
Freeze-thaw resistance	ASTM C 666 (Procedure A)	100% RDM @ 300 cycles
Scaling resistance	ASTM C 672	0 rating – no scaling @ 25 cycles
Slant shear bond strength	ASTM C 882 (modified[1])	2,300 psi (16 MPa) @ 1 day 2,600 psi (18 MPa) @ 28 days
Splitting tensile strength	ASTM C 496	400 psi (3 MPa) @ 1 day 450 psi (3 MPa) @ 28 days
Flexural strength	ASTM C 348	700 psi (5 MPa) @ 1 day 850 psi (6 Mpa) @ 28 days
Compressive strength	ASTM C 109	2,000 psi (14 MPa) @ 1 hr. 3,000 psi (21 MPa) @ 2 hr. 6,500 psi (45 MPa) @ 1 day 8,000 psi (55 MPa) @ 28 days
Compressive strength	ASTM C 39	7,400 psi (51 MPa) @ 28 days

[1] No bonding agent used; mortar scrubbed into substrate.

All application and performance values are typical for the material, but may vary due to variations in the test method, conditions, and configurations.

Order Information

Packaging

10-60 Rapid Mortar

- 50 lb. (22.7 kg) bag
- 3,000 lb. (1,361 kg) bulk bag

Shelf Life

- 10-60 Rapid Mortar has a shelf life of 9 months when transported and stored in cool, dry conditions between 40°F (4°C) and 85°F (29°C) in the original, unopened containers.

Coverage

- 0.43 ft.^{3} (0.012 m^3) per 50 lb. (22.7 kg) bag
- Extended 50% - 0.57 ft^3 (0.016 m^3)
- Extended 100% - 0.77 ft.^{3} (0.022 m^3)

Caution

10-60 Rapid Mortar contains crystalline silica, Portland cement, hydraulic cement, lithium carbonate

Risks

Product is alkaline on contact with water and may cause injury to skin or eyes. Ingestion or inhalation of dust may cause irritation. Contains free respirable quartz, which has been listed as a suspected human carcinogen by NTP and IARC. Repeated or prolonged overexposure to free respirable quartz may cause silicosis or other serious and delayed lung injury.

Precautions

KEEP OUT OF THE REACH OF CHILDREN. Prevent contact with skin and eyes. Prevent inhalation of dust. DO NOT take internally. Use only with adequate ventilation. Use impervious gloves, eye protection and if the TLV is exceeded or is used in a poorly ventilated area, use NIOSH/MSHA approved respiratory protection in accordance with applicable federal, state and local regulations.

First Aid

In case of eye contact, flush thoroughly with water for at least 15 minutes. SEEK IMMEDIATE MEDICAL ATTENTION. In case of skin contact, wash affected areas with soap and water. If irritation persists, SEEK MEDICAL ATTENTION. Remove and wash contaminated clothing. If inhalation causes physical discomfort, remove to fresh air. If discomfort persists or any breathing difficulty occurs or if swallowed, SEEK IMMEDIATE MEDICAL ATTENTION.

For more information see Material Safety Data Sheet (MSDS) for this product.

Proposition 65

This product contains material listed by the state of California as known to cause cancer, birth defects or other reproductive harm.

VOC Content

This product contains 0 g/L or 0 lbs./gallon.

For medical emergencies only, call ChemTrec (1/800/424-9300).

Limited Warranty Notice

Every reasonable effort is made to apply ChemRex® exacting standards both in the manufacture of our products and in the information which we issue concerning these products and their use. We warrant our products to be of good quality and will replace or, at our election, refund the purchase price of any products proved defective. Satisfactory results depend not only upon quality products, but also upon many factors beyond our control. Therefore, except for such replacement or refund, ChemRex® MAKES NO WARRANTY OR GUARANTEE, EXPRESS OR IMPLIED, INCLUDING WARRANTIES OF FITNESS FOR A PARTICULAR PURPOSE OR MERCHANTABILITY, RESPECTING ITS PRODUCTS, and ChemRex® shall have no other liability with respect thereto. Any claim regarding product defect must be received in writing within one (1) year from the date of shipment. No claim will be considered without such written notice or after the specified time interval. User shall determine the suitability of the products for the intended use and assume all risks and liability in connection therewith. Any authorized change in the printed recommendations concerning the use of our products must bear the signature of the ChemRex® Technical Manager.

ThoRoc™
Concrete Restoration Solutions

ChemRex®

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Appendix D6- Five Star® Fast Set Cement

FIVE STAR® FAST SET CEMENT

Field Mix Concrete

PRODUCT DESCRIPTION

Five Star Fast Set Cement is a fast setting, specially formulated hydraulic cement used to produce fast setting concrete or mortar for horizontal repairs in traffic areas. Concrete or mortar made with Five Star Fast Set Cement produces high early strengths as well as ease of workability required by the transportation industry. Five Star Fast Set Cement is field mixed into a mortar or concrete, ideal for use in a volumetric mixer.

ADVANTAGES

- Ability to customize field mix
- High early strength
- Open to traffic in two hours
- Freeze/thaw resistance
- Adjustable working time

USES

- Airport runways and taxiways
- Highways and bridges
- Parking decks and ramps
- General repair of concrete structures
- Expansion joint rebuilds
- Steps and sidewalks

TECHNICAL SUPPORT

Five Star Products maintains the industry's foremost Engineering and Technical Support Group:

- Over 30 years of experience in concrete repair
- Technical Center staffed with experienced engineers available for consultation
- Design-A-Spec™ for engineering specification assistance
- Experienced representatives for field service
- Corporate research laboratory available to customize products for unique applications

PACKAGING

Five Star Fast Set Cement is available in heavy-duty polyethylene lined bags weighing 94 lb (42.6 kg) or bulk bags weighing 2500 lb (1136 kg).

TRIAL MIX DESIGN

Mix Design(1)

	One Bag lb	One Cubic Yard lb
Fast Set Cement	94	728
Concrete Sand (2)	178.3	1382
3/8" Pea Gravel (2)	218	1689
Water (3)	28.2 to 32.9	218.4 to 254.8
Admixtures (4)		
Slump	3 to 6 inches (75 mm to 150 mm)	

(1) These are suggested SSD starting weights. Final quantities shall be based on fine and coarse aggregate which is available at the job site.

(2) Aggregate must meet the requirements of ASTM C 33.

(3) Net potable water added should be adjusted to control slump to within 3 to 6 inches (75 to 150 mm). Do not exceed a maximum water:cement ratio of 0.45.

(4) Air entraining and retarding admixture may be added for specific job requirements and weather conditions. Trial mixes should be performed to finalize dosage and mix design.

TYPICAL PROPERTIES AT 73°F (23°C) OF TRIAL MIX DESIGN

Compressive Strength, ASTM C 39	
2 Hours	2000 psi (13.8 MPa)
1 Day	3500 psi (24.2 MPa)
28 Days	6000 psi (41.4 MPa)
Length Change, ASTM C 157	
28 Days Wet	+0.03%
28 Days Dry	- 0.03%
Time of Set, ASTM C 266	
Initial Set	15-25 minutes
Final Set	20-30 minutes
Freeze/Thaw Resistance, ASTM C 666A	
Relative Durability Factor	> 90%
Flexural Strength, ASTM C 78	
3 Hours	350 psi

The data shown above reflect typical results based on laboratory testing under controlled conditions using selected aggregates. Variations from the data shown above may result based on aggregates used. Test methods are modified where applicable.

PLACEMENT GUIDELINES

1. SURFACE PREPARATION: All surfaces in contact with fast setting concrete shall be free of oil, grease, laitance, and other contaminants. Concrete must be clean, sound and rough to ensure a good bond. Remove all oxidation from exposed reinforcing steel and for additional protection coat reinforcing steel with Five Star® AC Coat. A perimeter edge and minimum depth of one inch (25 mm) for mortar or two inches (50 mm) for concrete should be provided for a durable repair. Featheredging is not recommended. Soak concrete surfaces prior to application with liberal quantities of potable water, leaving the concrete saturated and free of standing water or use Five Star® Bonding Adhesive. Surfaces shall be conditioned to between 40°F and 90°F (4°C to 32°C) at the time of placement.
2. MIXING: Small batches of concrete or mortar using Five Star Fast Set Cement may be mixed in a mortar mixer. Pre-wet the mortar mixer with potable water and empty excess water. Add 28 lb water per 94 lb bag of cement into the mixer. With the mixer turning, slowly add dry ingredients (cement and fine aggregate, then coarse aggregate) called for by the final mix design, and mix to a uniform consistency. Add only as much water as is needed to adjust the consistency to a slump of 3 to 6 inches. Do not exceed a water:cement ratio of 0.45. Do not mix more material than can be placed 10 minutes.

   For large quantities, use a volumetric mixer. Adjust the mixer to deliver and mix ingredients in the proportions called for by the final mix design. Adjust the water to give a slump of 3 to 6 inches. Do not exceed a water:cement ratio of 0.45.
3. PLACEMENT PROCEDURES: Firmly work Five Star Fast Set Cement concrete or mortar into substrate and place full depth from one side of the repair to the other. Where this is not practical, placement must be continuous to prevent cold joints between pours. Finish as necessary.

   SPECIAL CONDITIONS: For use in cold temperatures, fast setting concrete must be maintained at a temperature of at least 35°F (2°C). Protect from freezing until a compressive strength of at least 1000 psi (6.9 MPa) is obtained. Faster strength gain will occur when the mix temperature of the fast setting concrete has been conditioned to 60°F to 70°F (15°C to 21°C) prior to placement.

   In hot temperatures, fast setting concrete should be kept as cool as possible, but not exceeding 80°F (26°C) unless a retarder is used. Chilled water should be used for mixing to help maintain sufficient working time.
4. POST-PLACEMENT PROCEDURES: Five Star Fast Set Cement concrete or mortar shall be protected from excessive evaporation until initial set, then immediately coat with an approved curing compound meeting water retention properties of ASTM C 309 or wet cure for a minimum of three days. In-service operation may begin immediately after the required strength has been reached.

   NOTE: PRIOR TO APPLICATION, READ ALL PRODUCT PACKAGING THOROUGHLY. For more detailed placement procedures, refer to DESIGN-A-SPEC™, or call the Five Star Products Engineering and Technical Center at 800-243-2206.

LIMITATIONS

- Never exceed the maximum water:cement ratio of 0.45.
- Temperature of surfaces must be between 40°F and 90°F (4°C and 32°C) at time of placement.
- Substrate shall be free of frost and ice.
- Repair material shall be protected from freezing until it reaches 1000 psi (6.9 MPa).
- Placement shall be continuous to prevent cold joints.

CAUTION

Contains cementitious material. International Agency for Research on Cancer has evaluated there is sufficient evidence for the carcinogenicity of inhaled crystalline silica to humans. Take appropriate measures to avoid breathing dust. Avoid contact with eyes and contact with skin. In case of contact with eyes, immediately flush with plenty of water for at least 15 minutes. Immediately call a physician. Wash skin thoroughly after handling. Keep product out of reach of children. PRIOR TO USE, REFER TO MATERIAL SAFETY DATA SHEET.

WARRANTY: "FIVE STAR PRODUCTS, INC. (FSP) PRODUCTS ARE MANUFACTURED TO BE FREE OF MANUFACTURING DEFECTS AND TO MEET FSP'S CURRENT PUBLISHED PHYSICAL PROPERTIES WHEN APPLIED IN ACCORDANCE WITH FSP'S DIRECTIONS AND TESTED IN ACCORDANCE WITH ASTM AND FSP STANDARDS. HOWEVER, SHOULD THERE BE DEFECTS OF MANUFACTURING OF ANY KIND, THE SOLE RIGHT OF THE USER WILL BE TO RETURN ALL MATERIALS ALLEGED TO BE DEFECTIVE, FREIGHT PREPAID TO FSP FOR REPLACEMENT. THERE ARE NO OTHER WARRANTIES BY FSP OF ANY NATURE WHATSOEVER, EXPRESSED OR IMPLIED, INCLUDING ANY WARRANTY OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE IN CONNECTION WITH THIS PRODUCT. FSP SHALL NOT BE LIABLE FOR DAMAGES OF ANY SORT, INCLUDING PUNITIVE, ACTUAL, REMOTE OR CONSEQUENTIAL DAMAGES, RESULTING FROM ANY CLAIMS OF BREACH OF CONTRACT, BREACH OF ANY WARRANTY, WHETHER EXPRESSED OR IMPLIED, INCLUDING ANY WARRANTY OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE OR FROM ANY OTHER CAUSE WHATSOEVER. FSP SHALL ALSO NOT BE RESPONSIBLE FOR USE OF THIS PRODUCT IN A MANNER TO INFRINGE ON ANY PATENT HELD BY OTHERS."

For worldwide availability, additional product information and technical support, contact your local Five Star distributor, local sales representative, or you may call Five Star's Engineering and Technical Center at 800-243-2206.

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Appendix D7- AHT-Highway DB Retrofit Mortar™

TECHNICAL BULLETIN

AHT - HIGHWAY DB RETROFIT MORTAR™

Rapid Set, High-Early Strength Repair Mortar

V O C compliant

Product Description:
AHT Highway DB Retrofit Mortar is a rapid setting, high-early strength repair material that produces a permanent repair for concrete. AHT Highway DB Retrofit Mortar can be used neat or extended up to 100% with coarse aggregates.

Typical Applications:
Full or partial depth restoration of:

- Highways and roadways
- Bridge Decks
- Manufacturing, storage and shipping areas
- Parking garages, decks, ramps and lots
- Bridge nosings
- Commercial freezers
- Roadway joint restoration
- Aisles
- Distribution center and warehouse floors
- Bridge and Highrise railing grouting
- Airport installations

Feature/Benefits:

- Meets or exceeds requirements of ASTM C 928 - 92a
- Rapid, high-early strength gain
- Reaches 4000 psi (27 Mpa) in 3 hours
- Freeze/thaw resistant
- Wide temperature use
- Early return of traffic
- Easy to place
- Excellent bond to concrete substrate
- Expands and contracts at a similar rate to concrete

Technical Data:
All data has been derived under laboratory conditions. Field conditions and variations in amounts and types of aggregates may yield slightly different results.
Test data derived using mortar (no stone)
ASTM C-109

Compressive Strength, ASTM C 928:

	72ºF - (psi)	(22ºC) - (Mpa)
3 hrs.	4000	27
1 day	6500	45
7 day	8000	55
28 day	10000	69

Length Change, ASTM C 157: (w/ASTM C 928 modifications)

	72ºF (22ºC)	
	Air Cured	Water Cured
28 days	-0.09%	0.018%

Set Times, ASTM C 191: Concrete Mix

Initial: 25 minutes
Final: 35 minutes

Flexural Strength, ASTM C 348:
1 Day: 1000 psi (6.9 MPa)
28 Days: 1250 psi (8.6 MPa)

Splitting Tensile, ASTM C 496:
1 Day: 565 psi (3.9 MPa)
28 Days: 764 psi (5.2 MPa)

Slant Shear Bond, ASTM C 882 (modified):
1 Day: 2500 psi (17 MPa)
28 Days: 4000 psi (27 MPa)

Modulus of Elasticity, ASTM C 469:
5.8 X 10^6

Chloride Permeability, ASTM C 1202:
155.7 Coulombs, VERY LOW

Scaling Resistance, ASTM C 672:
25 Cycles: NO SCALING

Chemical Analysis

1. Sulfate content, CA DOT TEST METHOD 417: <30mg/kg (<0.003%)
2. Chloride content, CA DOT TEST METHOD 422: 27 mg/kg (0.0027%)

Freeze/Thaw, ASTM C 666A
Durability Factor@ 300 CYCLES: 95%

Caltrans Test Method 551, Bond Strength
Meets requirements for both DRY and SSD PCC

Application Instructions Preparation:
Proper repairs depend upon a solid bond between the mortar and base surface!

Thoroughly clean and roughen subject area. Remove any curing compound, grease, oil, loose or carbonated concrete, dirt, dust, etc. from exposed slab. Saw-cut area perimeter to a depth of at least 1/2" (12 mm). Roughen the smooth surface left behind after saw-cutting. Use water under moderate pressure to flush and further clean area.

If possible, saturate area for 24 hours prior to applying mortar. During application, area should be saturated, but free of any standing water.

AMERICAN HIGHWAY TECHNOLOGY®

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AHT - HIGHWAY DB RETROFIT MORTAR™

Rapid Set, High-Early Strength Repair Mortar

Application, Surface Preparation, cont.

Maintain integrity of any abutting joints by using expansive joint material, bond breakers, polyethylene, isolation joint material, etc. to avoid bonding to adjacent slab.

If reinforcing steel has rusted or is not bonded to concrete, remove surrounding concrete to a depth of 1/2" (12mm) below the steel. Clean area of all chipped, disintegrated or broken concrete. Remove rust from reinforcing steel.

Typical Mixing Proportions and Yield:

Concrete Mix: 1 Cubic Yard, .7646 M^3*

AHT Highway DB Retrofit Mortar:	1875 lbs. (850 kg)
3/8" Stone	1875 lbs. (850 kg)
Water	25.25-28 gal (95-106 liters)

* Approximate, Bulk density of local aggregates will vary yield.

Concrete Mix: 100 Lbs., 45 kg

AHT Highway DB Retrofit Mortar:	50 lbs. (22.7 kg)
3/8" Stone	50 lbs. (22.7 kg)
Water	2.75-3.0 Qts. (2.6-2.8 liters)

Use only clean, washed, well graded sand and stone conforming to ASTM C-33. Do not use stone for repairs less than 2" (5 cm) in depth.

Ambient and Substrate Temperature Considerations:

Hot weather when ambient and/or base concrete temperatures are over 80ºF (26.5ºC): Protect applied material from direct sunlight. Apply cool water to work area. Use cool mixing water.

Cold weather when ambient and/or base concrete temperatures are below 45ºF (7ºC): Use warm mixing water. Protect installed HP MORTAR by covering with polyethylene or curing blankets. Follow ACI placement procedures for hot and cold weather conditions.

Mixing:

Place mixers close to repair area. Approximate initial set of AHT Highway DB Retrofit Mortar is 25 minutes at 72ºF (22.5ºC). Therefore, mix only an amount that can be placed and finished before initial set.

Place recommended amount of clean water into mixer. Add AHT Highway DB Retrofit Mortar MIXED WITH 3/8" STONE, mix and place. Discard any material that stiffens. Do not retemper.

Placing:

Scrub mixed material onto dampened surface, and then, work material aggressively into repair surface and around sides assuring good bond. Work from one side of site only -- not toward middle from opposite directions.

Finishing:

Level and screed material to proper height. Float edges with wooden or magnesium floats. Occasionally clean all tools of built-up material. Broom or tine, if desired, immediately after placing and prior to initial set.

Curing:

Above 45ºF (7ºC), apply wet burlap, rags, etc. to finished repair area and cover with polyethylene or, apply a membrane-curing compound approved. Below 45ºF (7ºC) for emergency repair situations, cover with polyethylene and keep warm until final set. Follow ACI recommended curing procedures.

Packaging:

AHT Highway DB Retrofit Mortar is supplied in 50 lb. (22.7 kg) paper bags, reinforced with 1 mil polyethylene inner lining to ensure moisture resistance. Delivery in 2,500# (1134 kg) bulk bags or tank delivery is available.

Precautions:

- Store under dry conditions.
- DO NOT use this product if bag is damaged or broken.
- DO NOT ADD admixtures (accelerators, water reducers, etc.) or antifreeze to this product.
- DO NOT ADD limestone, fly ash, silica fume, aggregate fines, cement or calcareous aggregate.
- DO NOT featheredge.
- DO NOT use for patches less than 1/2" (12 mm) deep.
- Consult AHT for any applications not mentioned above, when questionable conditions may prevail or for additional information.
- Follow ACI standards when placing in cold and hot weather.
- Ideal application range is between 40ºF (4.5ºC) and 90ºF (32ºC).
- DBR MORTAR should not be placed on hot substrates over 90ºF (32ºC) or under 40ºF (4.5ºC).
- Portland cement may cause irritation. Avoid contact with eyes and prolonged contact with skin.

Color:

AHT Highway DB Retrofit Mortar is concrete gray/brown in color and looks similar to concrete after curing.

Technical Services:

Call our technical staff for assistance at the numbers listed on the front page.

WARRANTY

AHT warrants only that this product meets the quality and technical standards noted in its current product literature. AHT cannot be held responsible for circumstances outside its control including, but not limited to; other materials, product handling, product storage or use of the product. AHT will provide sufficient product to replace any which is proven, by accepted Industry standard testing methods, to have manufacturing defects. Such product replacement shall constitute the sole and exclusive remedy. For any claim under this warranty. This warranty is in lieu of any other Warranties, expressed, implied or statutory and is strictly limited to its terms.