Use of Chemical Admixtures in Roller-Compacted Concrete for Pavements

National Concrete Pavement
Technology Center

Tech Center

Final Report
May 2013

Sponsored through
Federal Highway Administration (DTFH61-06-H-00011 (Work Plan 11))
Portland Cement Association (PCA)

IOWA STATE UNIVERSITY
Institute for Transportation

About the National CP Tech Center

The mission of the National Concrete Pavement Technology Center is to unite key transportation stakeholders around the central goal of advancing concrete pavement technology through research, tech transfer, and technology implementation.

Disclaimer Notice

Iowa State University Non-Discrimination Statement

Technical Report Documentation Page

1. Report No.
DTFH61-06-H-00011 Work Plan 11

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Use of Chemical Admixtures in Roller-Compacted Concrete for Pavements

5. Report Date
May 2013

6. Performing Organization Code

7. Author(s)
Chetan V. Hazaree, Halil Ceylan, Peter Taylor, Kasthurirangan Gopalakrishnan, Kejin Wang, and Fatih Bektas

8. Performing Organization Report No.
DTFH61-06-H-00011 Work Plan 11

9. Performing Organization Name and Address
National Concrete Pavement Technology Center
Iowa State University
2711 South Loop Drive, Suite 4700
Ames, IA 50010-8664

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Organization Name and Address
Portland Cement Association
5420 Old Orchard Road
Skokie, Illinois 60077

Federal Highway Administration
U.S. Department of Transportation
1200 New Jersey Avenue SE
Washington, DC 20590

13. Type of Report and Period Covered
Final Report

14. Sponsoring Agency Code
DTFH61-06-H-00011 Work Plan 11

15. Supplementary Notes
Visit www.intrans.iastate.edu for color PDF files of this and other research reports.

16. Abstract

Use of roller compacted concrete (RCC) for pavement applications is growing in the United States. This material offers great technical and economic benefits, however there is insufficient research done to understand it better. The drier consistency and lack of adequate paste in RCC makes its fresh behavior very different from other types of concretes. This also leads to challenges in characterizing its properties adequately to be translated to practice. The use of chemical admixture in RCC has not been studied in detail before and hence there is an apprehension in using them. What further aggravates the problem is the use of multiple mixing technologies used in producing RCC.

This research attempts to resolve some of these problems. The workability of concrete is considered to be constituted by the cohesion, compactibility, and segregation resistance, retention of workability, water reduction and consistency. Each of these properties was characterized using a test method. These include the use of vibrated slump test, direct shear test as used in soils, and gyratory compaction test as used in asphalt industry.

Furthermore, ten most widely used chemical admixtures were tested in a typical RCC mixture. These include water reducers, retarders, air entraining agents and dry cast industry products. For each of these product types, different chemical formulations were selected to evaluate the comparative performances. It is observed that individually each admixture offers distinct benefits and improves different properties of fresh RCC including changing the setting behavior and finishibility. Moreover, for a given mixture, the improvement in workability is a composite function of its components viz. cohesion, compactibility, consistency, water reduction, admixture type and dosage.

Finally, a set of recommendations are offered along with some precautions to be taken in using these admixtures individually. It is anticipated that this work will lead to the better characterization of different properties of RCC and use of chemical admixtures with greater confidence.

17. Key Words
air entraining agent—cohesion—compactibility—compressive strength—dry cast—roller-compacted concrete—water reducer—workability

18. Distribution Statement
No restrictions.

19. Security Classification (of this report)
Unclassified.

20. Security Classification (of this page)
Unclassified.

21. No. of Pages
53

22. Price
NA

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

USE OF CHEMICAL ADMIXTURES IN ROLLER-COMPACTED CONCRETE FOR PAVEMENTS

Final Report
May 2013

Principal Investigator
Halil Ceylan
Associate Professor
Institute for Transportation, Iowa State University

Co-Principal Investigators
Kasthurirangan Gopalakrishnan
Research Assistant Professor
Institute for Transportation, Iowa State University

Kejin Wang
Associate Professor
Institute for Transportation, Iowa State University

Research Assistant
Chetan V. Hazaree

Authors
Chetan V. Hazaree, Halil Ceylan, Peter Taylor, Kasthurirangan Gopalakrishnan, Kejin Wang, and Fatih Bektas

Sponsored by
Portland Cement Association
Federal Highway Administration
(DTFH61-06-H-00011 Work Plan 11)

A report from
National Concrete Pavement Technology Center
Iowa State University
2711 South Loop Drive, Suite 4700
Ames, IA 50010-8664
Phone: 515-294-8103
Fax: 515-294-0467
www.intrans.iastate.edu

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

The financial support received from the Portland Cement Association (PCA) and the Federal Highway Administration (FHWA) is sincerely acknowledged. Various material suppliers including the cement, fly ash, and various admixture suppliers were very enthusiastic in supporting this test program during its tenure. Their contribution to this work was very meaningful. Bob Steffes, with the National Concrete Pavement Technology Center (National CP Tech Center) earnestly supported the laboratory testing at different phases of this work. Technical discussions with Clarissa Ferraris, Ara Jeknavorian, Ketan Sompura, and Caroline Talbot were very effective and are gratefully acknowledged. Thanks are also due to Wayne Adaska, William (Tim) McConnell, and Steve Kosmatka with the PCA and Tom Cackler with the National CP Tech Center.

EXECUTIVE SUMMARY

This research focused on the use of chemical admixtures in RCC. The workability of concrete is considered to be constituted by its cohesion, compactibility, and segregation resistance, retention of workability, water reduction and consistency. Each of these properties was characterized using a test method. These include the use of vibrated slump test, direct shear test as used in soils, and the gyratory compaction test.

Ten widely used chemical admixtures were tested in a typical RCC mixture. These include water reducers, retarders, air entraining agents and dry cast industry products. For each of these product types, different chemical formulations were selected to evaluate their comparative performance. It was observed that individually, each admixture offers distinct benefits and improves different properties of fresh RCC including changing the setting behavior and finishability. Moreover, for a given mixture, the improvement in workability is dependent on other factors such as cohesion, compactibility, consistency, water reduction, admixture type and dosage. It is anticipated that this work will lead to better characterization of different properties of RCC and use of chemical admixtures with greater confidence.

1. INDUSTRIAL CONTEXT AND SCOPE OF WORK

Roller-compacted concrete (RCC) is a special mixture of controlled, dense-graded aggregates, portland cement and possibly pozzolans (fly ash), mixed with just enough quantity of water so that it could self-stand when paved using either a slip-form paver (without needle vibrators) or asphalt paver. It is usually compacted using vibratory roller. Once compacted to the required density, RCC is cured using conventional methods. It has constituent materials similar to routine concrete, but is handled more like granular materials or soils. Due to dense packing, RCC renders itself as a high strength material that can be utilized in different pavement applications. Typical applications include low-maintenance roads, parking lots, industrial roads, intersections, city streets, heavy-duty pavements, airport pavements, pavement bases, and pavement shoulders. RCC applications have been expanding in United States (refer to Figure 1-1).

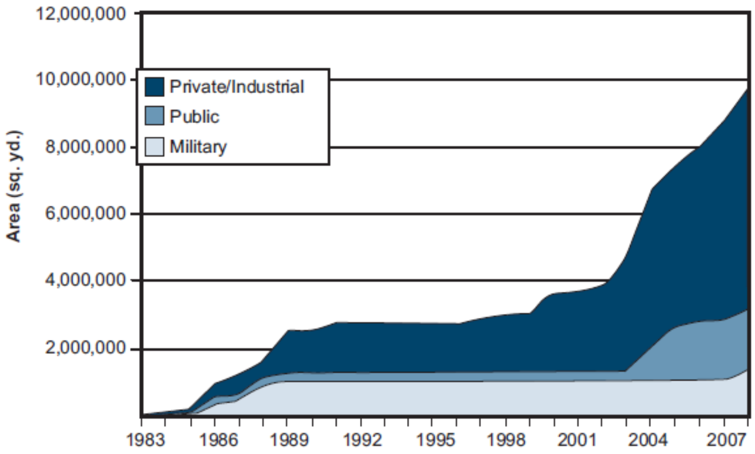


Figure 1-1. Growth in RCC applications in United States (Pittman and Anderton, 2009)

When compared to conventional pavement and other types of concretes, RCC typically has a higher volume of aggregate withand lower binder and water contents, and hence, reduced paste volume. For a given binder content, RCC will typically offer higher strength than the corresponding conventionally compacted pavement concrete (CCPC). Aggregates used in CCPC can be used in RCC as long as there are sufficient fines in the mixture. It also needs to be noted that most of the CCPC's will be dosed with chemical admixtures like plasticizers, water reducers, retarders and air entrainers.

Apart from this, RCC pavement construction requires no jointing, reinforcement for load transfer (dowel bar), no formwork and can be easily rolled and finished. Thus, there is a potential for significant economic savings in materials and construction. Moreover, due to cement savings, RCC offers itself as a more sustainable material.

1.1 Current practices

The current practices can be divided into the following considerations:

1. Project level selection

2. Materials evaluation and selection
3. Production
4. Construction
5. Maintenance including troubleshooting

These considerations have been discussed in detail in the relevant publications on RCC (ACI Committee 325 1995; Service d'Expertise en Matériaux Inc. 2004; Hazaree 2006). The primary difficulties faced by practitioners are in terms of inadequate and consistent mixing, inability to use chemical admixtures with some mixers like pugmills, segregation, lack of a good method for assessing the consistency and compactibility, problems associated with insufficient compactibility, insufficient compaction time window, poor finishibility and typical problems associated with rolling compaction in terms of surface quality, among others. The following sub-sections offer an introduction to the related objectives of this work.

1.1.1 Use of different chemical admixtures

The use of chemical admixtures in RCC is somewhat limited. The primary reason being that RCC exhibits adequate mechanical properties, hence there has been little need to study the workability aspects of this concrete. It is also worth noting that the effectiveness of contemporary admixtures is relatively low in RCC when compared to other types of concretes. Moreover higher than normal or manufacturer recommended dosages are often required to obtain observable changes in the desired properties. This primarily occurs due to low water and paste content.

Water reducers and small dosages of superplasticizers are reported to improve the plasticity of concrete mixtures. However, the effectiveness of a water reducer dramatically reduces with a reduction in water content in the mixture. Retarders are used for extending the time window for roller compaction. Contradictory results are reported about the ability of different air entrainers in RCC (Service d'Expertise en Matériaux Inc. 2004). Recent investigations confirm a meaningful introduction of the air void system in RCC (Service d'Expertise en Matériaux Inc. 2004; Hazaree 2007) Most of these studies pertaining to the use of air entrainers were restricted to hardened concrete and its ability to resist freezing and thawing. A detailed investigation with an objective of understanding the role of these admixtures in changing the fresh properties of RCC is missing in the literature.

1.1.2 Characterizing workability

Workability, per se, is subjectively defined and is quite a controversial (Neville 1973) term. Neville (Neville 1995) comments that the technical literature abounds with variations of the definitions of workability and consistency but they are all qualitative in nature and more reflections of a personal viewpoint rather than of scientific precision. Tassios (Tassios 1973) recognizes that workability is an unreliable term and its exaggerated broadness of meaning does not help the expressiveness of the term. Due to diverse demands that different concretes place on some of the qualitative parameters (often quantifiable) that constitute the workability, it can be perceived not as a property but ever-changing optimization of other properties. Therefore, no definition of workability is presented here.

For dry concretes, relative density or compactibility, cohesion, and tendency to segregate are most important (Juvas 1996). RCC has drier consistency, making it difficult to reliably and consistently characterize its workability. A typical test method that is routinely used for RCC used in hydraulic structures is the Vebe time test as described in ASTM C1170 (ASTM 2008). Vebe time test is however criticized for its lack of discrimination, lack of consistency and subjective nature.

1.2 Research objectives

The objectives of this research are twofold:

1. To study the workability aspects of RCC:
    a. Characterizing different attributes of workability and
    b. Develop, evaluate and apply suitable test methods to characterize it
2. To study the effect of common chemical admixtures on the fresh and strength properties of RCC
    a. Retarders, water reducers, air entraining admixtures (AEA) and dry cast (DC) products and
    b. Combinations of these admixtures

The ultimate goal, in this regard, is to develop a suite of tests for evaluating the workability of RCC and to offer guidelines on admixture selection for typical concrete mixtures.

1.3 Scope of work

The research team defined the following tasks within the scope of the work:

1. Review industry practices and conduct a literature review of various chemical admixtures used in concretes with special reference to RCC;
2. Shortlist candidate test methods, evaluate and apply them in characterizing various aspects of workability of fresh concrete;
3. Perform laboratory investigations of most widely used chemical admixtures in typical RCC mixture;
4. Analyze the results and develop recommendations and guidelines for concrete producers and contractors.

Specific refinements to the proposed methods and tests results on actual sites will be required. This work specifically covers the laboratory investigation part and restricts itself from field trials or in-practice applications. It is anticipated that this work will help direct the preliminary admixture selection and offer some guidance on methods for characterizing the components of workability.

2. WORKABILITY OF CONCRETE AND ROLE OF CHEMICAL ADMIXTURES

Fresh concrete is a transitory phase of the ultimate material, but is fundamental in affecting the strength and long-term performance of the final concrete. The key properties of fresh concrete include ease of mixing, handling, transporting, laying, compacting to desired density, finishing to render a typically void-free, homogeneous and consistently dense mass. This mass upon hardening offers the desired performance. As discussed before, the workability of concrete is difficult to define and more often than not, the construction industry has been utilizing some empirical or semi-empirical tests to characterize one attribute of workability or the other. Recently the trend is shifting towards more mechanistic measurements like rheology. This chapter offers a synoptic overview of the literature on some of the attributes of workability and various chemical admixtures in brief.

2.1 Chemical admixtures

Chemical admixtures are ingredients other than water, aggregates, cementitious materials, and fiber reinforcement, added to the batch before or during its mixing to modify its freshly mixed, setting and hardening properties (ACI Committee 116 2000). Unlike supplementary cementitious materials, these are non-pozzolanic, mostly organic, physio-chemical in their actions and are normally supplied as water based solutions and suspensions (but could also be in powder form, dispersions and emulsions (Edmeades and Hewlett 1998)). The typical active chemical content is in the range of 35-40%. The dosage rate is generally less than 5% by mass of cement, albeit, the majority of admixtures are used in the typical range of 0.3-1.5% (Dransfield 2003). Although added in small quantities compared to the other constituents in concrete, these are of great value in economically enhancing several concrete properties and play a decisive role in sustainable development. Conventionally made from industrial by-products, the contemporary trend is shifting towards making chemical admixtures from synthetic polymers especially produced for the concrete industry (Aïtcin 2008).

The major categories of admixtures routinely used in concretes include plasticizers, normal water reducers, superplasticizers, retarders, retarding water reducers, and AEA's (Edmeades and Hewlett 1998). The ASTM standards covers chemical admixtures in two documents among others: ASTM C494 (ASTM 2008) and ASTM C260 (ASTM 2006). ASTM C494 covers the physical, general and performance requirements for water-reducing, retarding and accelerating admixtures. While ASTM C260 covers these requirements for AEA. The main admixture types are briefly described below. Specific chemistry and formulations are not discussed in this report, but specific literature (Ramachandran and Knovel (Firm) 1995; Rixom 1999) and other up-to-date publications contain abundant information on each of these.

Admixtures work by one or more of the following actions (Dransfield 2003):

1. Chemical interaction with the cement hydration process, typically causing an acceleration or retardation of the rate of reaction of one or more of the cement phases.
2. Adsorption onto cement surfaces, typically causing better particle dispersion (plasticizing or superplasticizing action).

3. Affecting the surface tension of the water, typically resulting in increased air content.
4. Affecting the rheology of the water, usually resulting in increased plastic viscosity or mix cohesion.

2.1.1 Water reducing admixtures

Cement particles are weakly bonded by electrostatic forces during early hydration; this state leads to locking up of water between cement particles and reduces the available surface area for hydration reactions to progress. This in turn leads to inefficient usage of cement in concrete. Water reducing admixtures adsorb on to the cement particles with a consequent lowering of inter-particular attraction so that agglomerates of cement break up. This produces a more uniform dispersion of cement grains reducing the amount of water required to achieve a given consistency. Due to the dispersion of the cement particles, the mixture is plasticized, more water is made available and hence the consistency can be improved. Depending on the amount of water reduction achieved, the water reducing admixtures are classified in ASTM C 494 as normal water reducing type or plasticizer (water reduction up to 12%) and high range water reducing type or superplasticizer (water reduction above 12%).

Normal water reducing admixtures (NWRA) or plasticizer

These are normally based on salts of lignosulphonic acids and their modifications, salts of hydrocarboxylic acids and their modifications, derived versions (Christensen and Farzam 2006) and other compounds. The water reducing effect offered by these admixtures can be utilized for either increasing the strength or saving cement or enhancing the workability of a mixture. The water reducing admixtures are adsorbed on to the cement particles and through electrical repulsion lower the inter-particular attraction so that flocs of cement break up. This produces a more uniform dispersion of cement grains reducing the amount of water needed to achieve a given paste viscosity. This is pictorially shown in Figure 2-1.

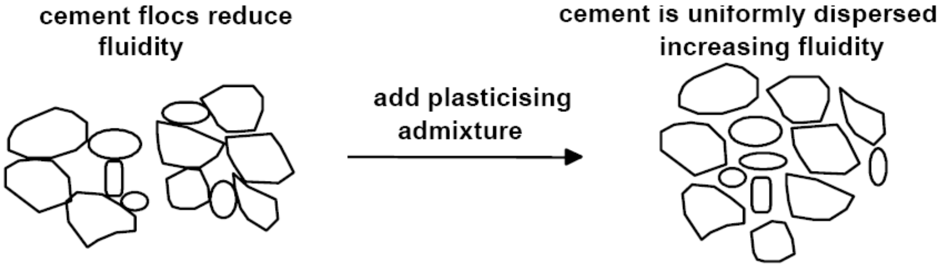


Figure 2-1. Schematic sketch of plasticizing mechanism (Dransfield 2006)

High range water reducing admixture (HWRA) or superplasticizer

Superplasticizers are broadly classified (Ramachandran and Malhotra 1995; Aïtcin 2008) into four major groups viz. Polymelamine sulphonates, Polynapthalenes, Lignosulphonates and Polycarboxylates. In addition to these superplasticizer groups, polyacrylates and phosphonates and other copolymers are also manufactured (Aïtcin 2008). SP’s improve the dispersion of cement particles furthermore by two different mechanisms viz. the electrical repulsion and the steric hindrance effects. This is pictorially shown in Figure 2-2. This results in increased dispersion of cement particles and hence higher water reduction and plasticification.

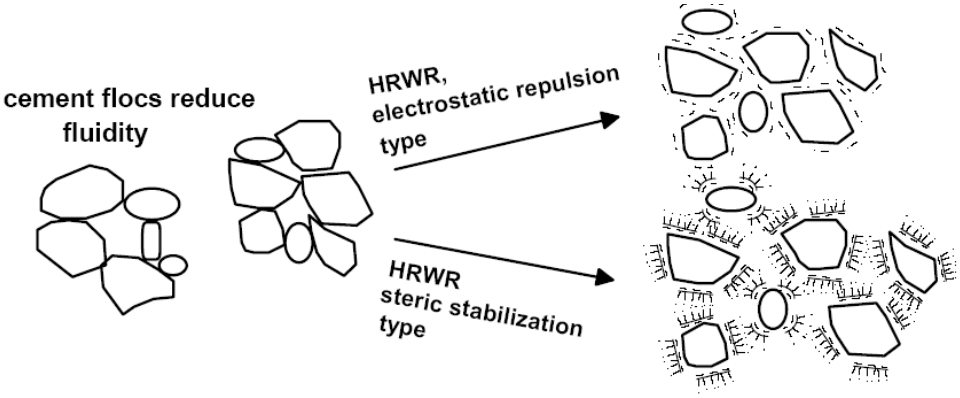


Figure 2-2. Schematic sketch of acting mechanism of superplasticizers (electrostatic and electrosteric) (Dransfield 2006)

Communications with some admixture manufacturing companies in United States revealed that the industry is quickly advancing towards using purified lignosulphonates (lignin-based), polycarboxylates (PC-based) and their blends only. The naphthalenes and the melamines are not widely manufactured or used by the industry any longer.

2.1.2 Retarding admixture or retarder

As the name suggests, these admixtures (mostly water-soluble) retard or slow the rate of cement hydration, preventing mixtures from setting before it is laid and compacted. Thus, these admixtures extend the time window within which the concrete can be worked with. These by themselves do not plasticize significantly and have little or no effect on the water demand or other properties of the concrete (Dransfield 2006). Consequences of this delay include a slowing of early strength development of concrete and an increase in the later strength. Usually it is observed that the long term strength is greater than the strength of non-delayed concrete (Aïtcin 2008) .

Salts of carboxylic acids are the most dominant type of retarders. Pure retarders (like that of ASTM type B) are occasionally applied and are infrequently available in the market. Instead, bi- or multi-functional admixtures (Type D, G) offering water reduction and/or plasticizing effect and retardation are quite popular. The basic chemistry of water reducers and retarders is similar in many aspects (Dodson 1990; Collepardi 1995; Vikan 2007). Hence, the working mechanics are quite similar. Other types of chemicals used for retarding admixtures include sucrose, other polysaccharides, citric acid, tartaric acid, salts of boric acid, salts of poly-phosphoric and phosphonic acids. In addition to these, the chemicals used for retarding-water reducing admixtures are hydroxyl-carboxylic acid salts, hydroxylated polymers and ligno sulfonic acid salts (Dransfield 2003; Dransfield 2006).

2.1.3 Air entraining admixture or AEA

Air entrainment achieved through the stabilizing action of air entraining admixture results in the formation of discrete, spherical, uniformly distributed air-voids or bubbles (ranging between 10 to 1000 μm) dispersed throughout the mixture. AEA's have traditionally been based on Vinsol resin (abietic acid salts) and fatty acid salts. These have now been largely replaced with synthetic surfactants based on blends of alkyl sulphonates, olefin sulfonates, diethanolamines, alcohol ethoxylates and betains (Dransfield 2006).

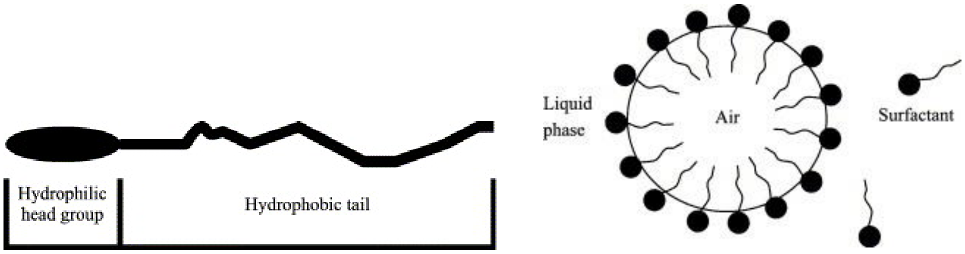


Figure 2-3. Basic chemical nature and the distribution of AEA surfactant molecules at the water-air interface (Du and Folliard 2005)

AEA's lower the surface tension of the water to facilitate bubble formation. Uniform dispersion is achieved by blending surfactants to increase the stability of the interfacial later between air and water, preventing bubbles from coalescing (Dransfield 2006). Figure 2-3 shows the basic chemical nature of surfactant based AEA and the distribution of surfactant molecules at the water-air interface.

2.1.4 Influencing factors

The chemical admixtures are physiochemically involved with the cement and/or binders. Their performance is thus intimately related to the properties of the binders. Refer to Figure 2-4 for a summary of some of these factors. Significant among these is compatibility of cement-admixture systems. Compatibility can be thought of as the ability of an admixture to ensure the desired level of performance while acting with given cement over a preset period. Compatibility could be related to materials (e.g. cement fineness, composition), ambient conditions (e.g. temperature, wind speed) and construction technology relation.

In case of AEA's factors like sand content, type and grading could play an influencing role. It is also interesting to note that the influence of one admixture could change dramatically in the presence of other admixtures. For example, the presence of certain AEA could significantly change the workability of a fresh concrete mixture containing a plasticizer.

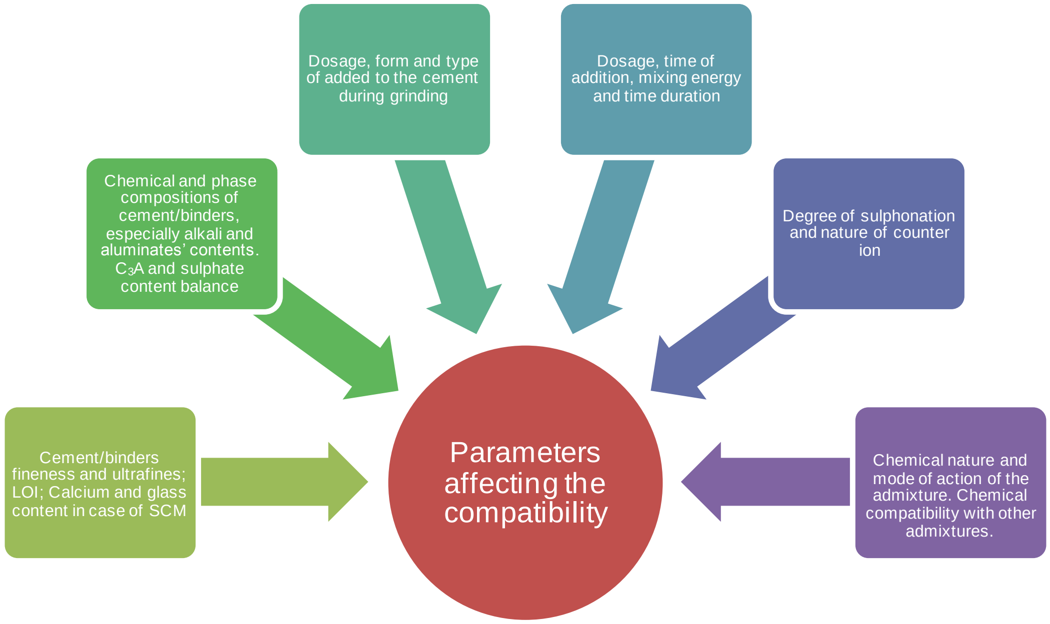


Figure 2-4. Factors affecting cement-chemical admixture compatibility

2.2 The effectiveness if admixtures in dry concrete mixtures

RCC offers unique set of challenges to the effective use of all chemical admixtures. Low water contents make it difficult for the admixtures to initiate their actions and effectively. As such, higher than normal admixture dosages are required. Manufacturer recommended dosages are for normal concretes and admixture manufacturers are reluctant to step outside the boundaries of safe dosages for multiple reasons, some being technical, others being ethical, societal and legal.

The mixer technology may also be critical in admixing some of the chemical admixtures into RCC. For example entraining air is a challenging task and cannot be effectually achieved using pugmills. Higher mixing energies, longer mixing cycles and reduced batch sizes are essential for admixing such concretes.

2.3 Workability of concrete: different aspects

A comprehensive summary of fundamental descriptions of workability offered by Ritchie (Ritchie 1968) is shown in Figure 2-5. As pointed out earlier, for drier concrete, compactibility, cohesion and segregation resistance are the most important properties. Due to the dry nature of these concretes, bleeding and viscosity are not so critical.

The consistency of RCC can be estimated using Vebe test. Other methods reported in the literature include the Cabrera slump test (Cabrera and Lee 1985), which is described in a later section.

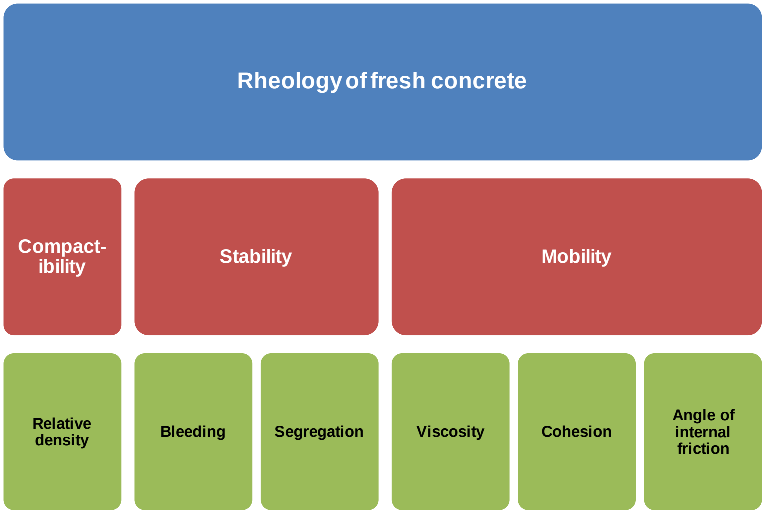


Figure 2-5. Factors influencing the rheology of concrete (Ritchie 1968)

Compactibility can be estimated using Proctor test, Vebe test, its modified versions and its derivatives (widely used for dam concretes) (Bureau of Indian Standards 1959; IS: 1199 (1959) 1959; Hansen and Reinhardt 1991; Kokubu, Cabrera et al. 1996), vibrating hammer (Juvas 1994; Bartos, Sonebi et al. 2002) and Waltz test. These methods are either subjective, and/or are cumbersome, tedious, slow, inaccurate, unable to differentiate small differences (Juvas 1996; Kappi and Nordenswan 2007) and show technically poor performance.

Researchers investigating the compactibility of drier concretes have looked at the intensive or gyratory compactor. These include Paakkinen (Paakkinen 1986), Juvas (Juvas 1987; Juvas 1990; Juvas 1994; Juvas 1996), Kappi and Nordenswan (Kappi and Nordenswan 2007) and Amer (Amer 2002). A gyratory compactor applies an axial pressure and a rotating gyratory shear deformation to a sample of material contained in a cylinder. Both the axial pressure and the shear deformation are applied through plates that are at a slight angle to the longitudinal axis of the cylinder. As the end of the plates rotate, the angle of the end plates produces a kneading action that compacts the sample in a reproducible manner. As the sample is compacted, reduction of volume is continuously calculated by measuring the height of the specimen. This also makes it possible to calculate the rate of volume change (rate of compaction) during the test. Figure 2-6 shows the working principle and typical density plots.

The deformation behavior of dry concretes can be modeled using Mohr-Coulomb model (Lambe and Whitman 1969; Alexandridis and Gardner 1981; Li 2007) often used for soils. The equation for Mohr-Coulomb failure criteria is given as follows:

$$\tau_f = c + N tan\varphi$$

where τ_f is the failure shear stress, c is the cohesion and φ is the angle of internal friction. Cohesion in concrete mainly manifests due to the chemical bonding resulting from the ongoing hydration reactions. Tassios (Tassios 1973), L'Hermite (L'Hermite 1949) and Popovics (Popovics 1982) have reported some work based on this principle. For this the triaxial test was observed to render higher than true values (Powers 1968), while direct shear test was used by the above mentioned investigators quite reliably.

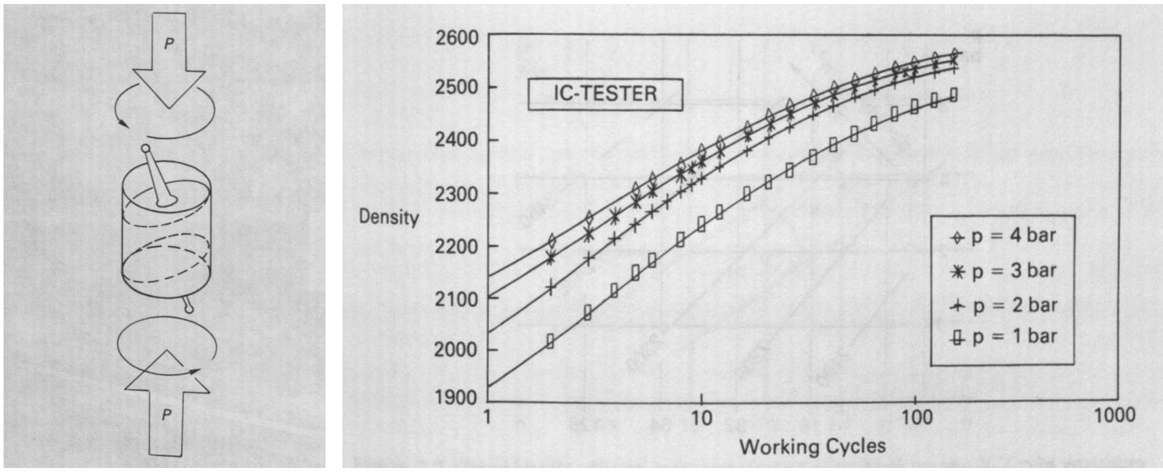


Figure 2-6. Schematic of intensive compactor and effect of working pressure on density (Paakkinen 1986)

3. EXPERIMENTAL WORK

This chapter describes the materials, methods and the basic mixture proportions used in this work. Furthermore, the test program for the admixed concretes is also described.

3.1 Materials

ASTM Type I cement and class F fly were used in this work. The physical properties and chemical constitution are reported in appendix AA. 19 mm nominal maximum size Limestone coarse aggregate and river sand were used as aggregates. The coarse aggregate met the grading specifications for size D67 of ASTM C33 (ASTM 2008). The bulk specific gravity and water absorption of coarse and fine aggregate were 2.676, 2.633 and 0.9%, 0.7% respectively. The Los Angeles abrasion value of coarse aggregate was 26%. The fineness modulus of river sand was 2.94. Tap water was used for mixing all the concrete mixtures.

31 different admixtures were initially procured for preliminary screening. Based on initial trials on cement paste, 10 admixtures were selected for use in this work. Table 3-1 shows the product codes, their principal chemical compound, recommended dosage and classification as per ASTM C494 and C260.

Table 3-1. Different chemical admixtures

Product Code	Primary chemical constitution	Functional classification							Reco. dosage (ml/100kg of cement)
		WR		Retarder			AEA	DC	
		ASTM C494 Type							
		A	F	B	D	G			
P-05	Polycarboxylate resin	▨	▨						341-650
P-06	Triethanolamine	▨							195-455
P-10	Ca-lignosulfonate	▨	▨	▨	▨	▨			NA
P-11	Lignin+Polymer	▨		▨	▨				130-390
P-13	Not available			▨	▨				130-260
P-19	Sodium olefin sulfonate						▨		30-60
P-20	Na-tetradecenesulfonate						▨		15-500
P-21	Tall oil/Na salt						▨		30-60
P-28	Surfactant							▨	130-390
P-29	PC resin + Polethylene glycol							▨	130-391

Since the naphthalenes and melamines are not that widely used in United States market, only lignin and polymer based water reducers were used. The products P-05 and P-10 were broad range products implying they could be used as type A, F products. Two retarding type water reducers (P-11 and P-13) were used. Three different AEA’s (P-19, P-20 and P-21) were used to evaluate their effects on compactibility and other fresh properties of concrete mixtures. Product P-19, -20 and -21 were synthetic detergent, water-soluble hydrocarbon and modified resin respectively. Above table gives also provides the manufacturer recommended dosages. Although these dosage ranges were used as guidelines, they were not strictly followed because it was anticipated that within this range the admixtures would not be effective in RCC mixtures.

3.2 Test methods

A vibrating compacting hammer was used for obtaining the moisture density plots and for casting the cylinders for compressive strength testing. To obtain the moisture density plot, an ASTM C 231 air-pot was used. Concrete was compacted in three equal lifts. For compressive strength, the cylinder was compacted in two layers.

Figure 3-1. Test procedure for measuring consistency: CSV

The Cabrera slump value (CSV) test consists of vibrating a slump cone filled with concrete (rodded in the same way as conventional concrete) and vibrating for 20 seconds. The drop of the concrete surface (slumping) is measured inside the slump cone. This reported slump is expressed in mm and is called as CSV. The developers of this test have reported a repeatability of ± 5% for this test (Cabrera and Lee 1985; Cabrera and Atis 1999). It is important to appreciate the fact that only concretes of very dry consistencies are tested using this method and the possible range of measurements could be very narrow (zero to 50-60mm). The CSV was recorded at 15 min after water is introduced in the mixture.

The gyratory compactor used for this work is shown in Figure 3-1. A review of published literature on possible ranges for various compaction parameters and feasibility with the available unit lead to the use of the following parameters. Consolidation pressure: 200 kPa, rate of gyration: 30 number/min, angle of gyration: 1.25, internal diameter of the mold: 150 mm and number of gyrations: variable. The compactibility responses were recorded at 15, 60 and 120 min after water was introduced in the mixture.

Figure 3-2. Gyratory compactor used in the work

A scaled-up direct shear box (DSB) shown in Figure 3-2 was used for measuring the shearing resistance of concrete. The dimensions of the lower box were 300 x 250 x 100mm, while that of upper box were 250 x 250 x 100 mm. A data-logger was programmed to record the shearing loads while the concrete mixtures were sheared at a displacement rate of 6.55 mm/min. Three normal loads were used to run a set of test. The compressive strengths were measured at 1st, 3rd, 7th, and 28th day.


12/05/2009

Figure 3-3. Direct shear test for concrete (all measurements between 15 - 30 min.)

3.3 Selection of mixtures

Considering the range of applications for RCC, a typical aggregate to binder ratio (A/B) of 7 was chosen. This gave a binder content close of 280 kg/m^3. Fly ash dosage was chosen to be 25 % by total weight of binder while cement occupied the remaining 75 %. The combined particle grading including the binder particle size distribution is shown in Figure 3-3.

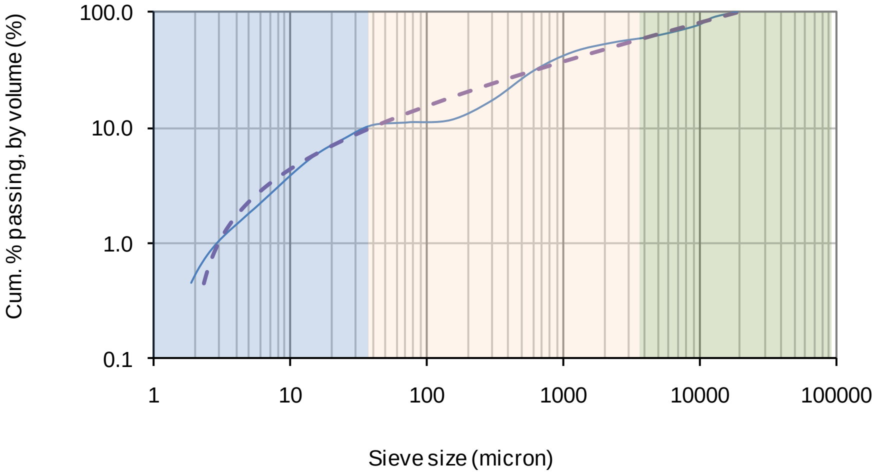


Figure 3-4. Combined particle grading (solid blue line shows actual grading for the used mixture)

With this fixed A/B, several moisture contents were used to obtain the moisture density plot. Based on this set of tests, the optimum moisture content (OMC) was 6.51% while the maximum dry density (MDD) was 2375 kg/m^3. The final mixture had the following composition in kg/m^3:

▪ Cement	:	212
▪ F type fly ash	:	70
▪ Aggregates	:	1998
▪ Water	:	131

Table 3-2. Experimental program for admixed concretes

Product Code	Admixture dosage (% by mass of cementitious materials)						Recommended dosage (%)
	1	2	3	4	5	6	
P-05	0.19	0.56	1.13	1.69	2.25	3.00	0.34-0.65
P-06	0.19	0.75	1.50	3.00			0.19-0.455
P-10	0.25	0.75	1.50	2.25	3.00		NA
P-11	0.25	1.00	2.00				0.13-0.39
P-13	0.20	0.60	1.20				0.13-0.26
P-19	0.08	0.19	0.38	0.70			0.03-0.06
P-20	0.15	0.30	0.75				0.015-0.50
P-21	0.08	0.19	0.38				0.030-0.060
P-28	0.25	0.75	1.50				0.13-0.39
P-29	0.25	1.00	2.00				0.13-0.39

This OMC-MDD mixture was used as a control mixture for the trials with different admixtures. The details of the admixed concrete trials are provided in Table 3-2. The admixture dosages used for this work were measured in terms of mass by mass of binder. Water reduction with respect to the control mixture (@OMC) was measured with admixed concrete while keeping the Cabrera slump value (CSV) constant. Other measured properties include the compactibility using gyratory compactor, the shear strength, cohesion and angle of internal friction using the direct shear box DSB and the compressive strength at various ages.

4. EFFECTS OF ADMIXTURES ON WORKABILITY AND STRENGTH

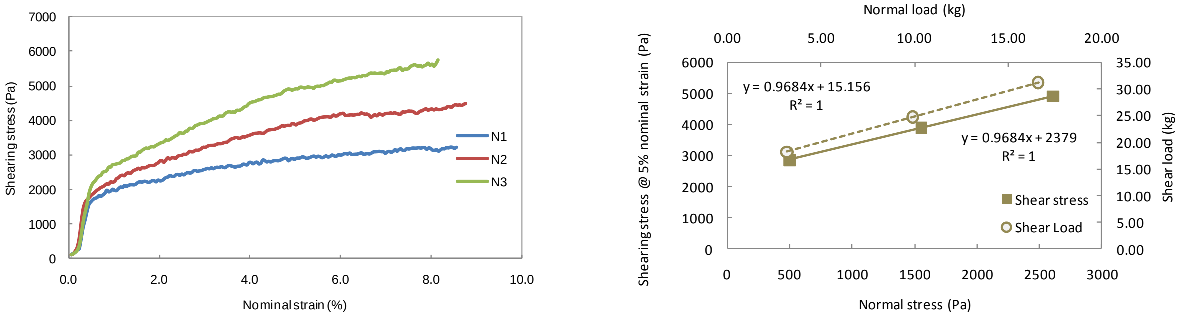
This chapter summarizes the results obtained from the experimental work. The properties for the non-admixed concretes are described in terms of the measured parameters followed by summaries of the properties of the admixed concretes.

4.1 Data analysis

The measured properties of concretes include the water reduction for a fixed consistency, air content, and cohesion, angle of internal friction, compactibility and compressive strength. Since the consistencies (CSV) of admixed concretes were kept constant, these are not reported here. The water reduction is computed as the percentage difference in water content with respect to the control concrete.

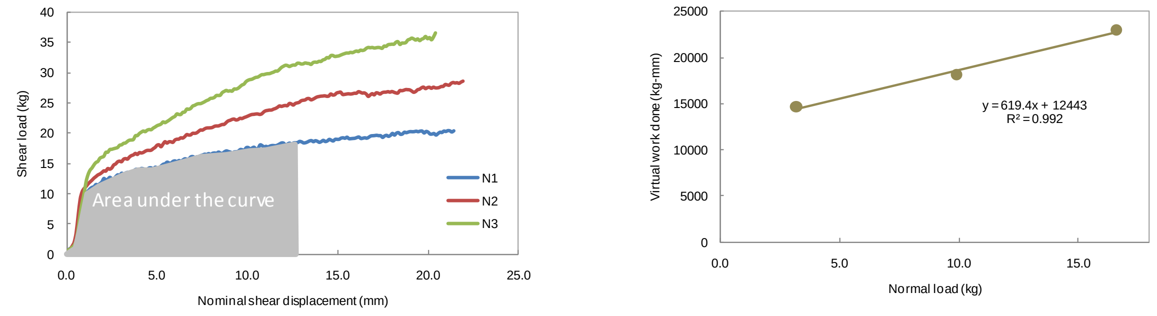
4.1.1 Cohesion and work indices

The analysis of the data obtained from the DSB test was similar to that done with geotechnical materials for getting the cohesion of fresh concrete. This is shown in Figure 4-1.



Shear displacement versus shear stress

Normal versus shear forces/stresses



Shear displacement versus shear load

Normal load versus virtual work done

Figure 4-1. Typical analysis of the shear strength data of fresh concrete

The area under each of the displacement-force curve was computed and was used in obtaining estimates of the work done. The area so computed from each of these plots was used in developing the normal load versus work done plot. This plot offers a relative idea about the roller compactibility of a concrete mixture with different static weight rollers. The slope of the line indicates the relative ease with which deformation can be achieved with increasing roller weights. A flatter line will indicate that there is not much advantage in increasing the static weight of a roller, while a steeper line will indicate that the concrete is relatively less workable with lesser roller weights, and hence the mixture needs to be improved in composition to achieve better compactibility and economy. This plot also gives an idea about the roller weight selection. While comparing two mixtures, a mixture that has a lower intercept on work-axis would mean the mix is readily compactable, while a higher intercept will mean that the mixture has lower compactibility and would require longer compaction times.

4.1.2 Compactibility

Typical density plots were obtained based on the data obtained from gyratory compactor. The data was further manipulated to come up with indices as shown in Figure 4-2.

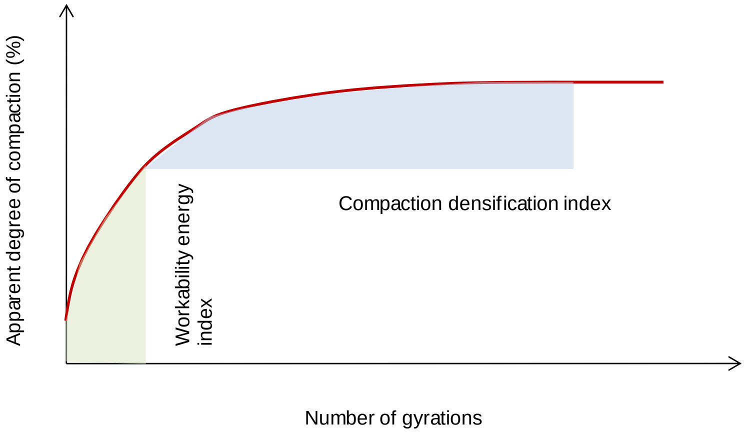


Figure 4-2. Definitions of compactibility indices

The Y-axis is computed as the percentage of the air free theoretical maximum density computed on volumetric basis. The horizontal axis is the number of gyrations, N. The Workability energy index (WEI) is defined as the area between the first and fifth gyratory compaction and is obtained by approximating the area under the relative compaction curve by the trapezoidal rule. The CDI on the other hand is shown considered to be the area above the relative compaction at N_5 and confined by N_5 and N_{20} and the relative compaction plot.

4.2 Non-admixed concrete

As discussed earlier, the aggregate binder ratio (A/B) was fixed at seven and the moisture content was varied to obtain the moisture density plot (refer to Figure 4-3). This is a typical behavior observed in RCC mixtures.

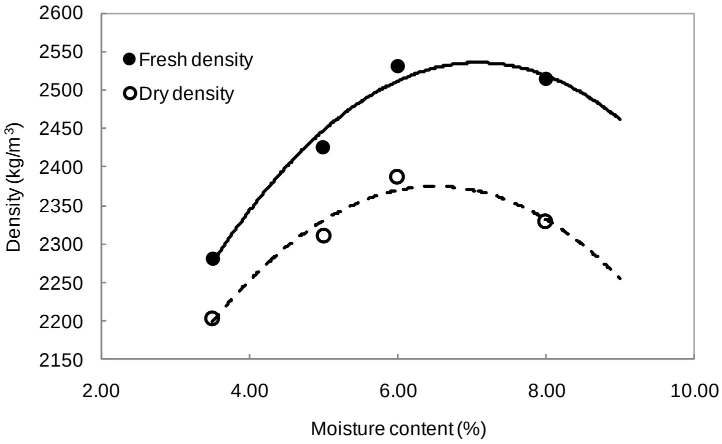


Figure 4-3. Moisture density plot

The trends in CSV and air content are shown in Figure 4-4. It was observed that initially due to less water, the concrete was not compactable and at the end of the specific compaction, effort left a considerable amount of air behind. This can be seen from the air content of the mixture. As the moisture content approached the OMC value, the compactibility of the concrete increased to reach the maximum value, while the air content reached a minimum.

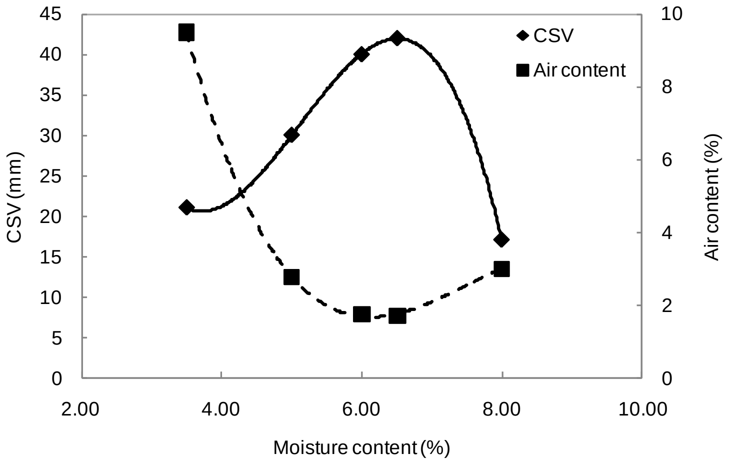


Figure 4-4. CSV and air content as affected by moisture content

The compressive strengths were measured at different ages. Figure 4-5 shows a plot of the 28-day strengths of these mixtures. This trend follows the moisture density plot. Initially due to low water content and hence drier consistency, the mixture is not fully compactable. Another term that is used in assessing the role of the binder in providing strength is the cementing efficiency factor (CEF), which is simply the ratio of the compressive strength divided by the binder content and multiplied by 100 at a given curing age. It can be seen that compaction and binder efficiency are linearly related. A better compaction will also lead to better strength gain. This term CEF will be frequently used in assessing the improvement in binding ability when admixtures are used.

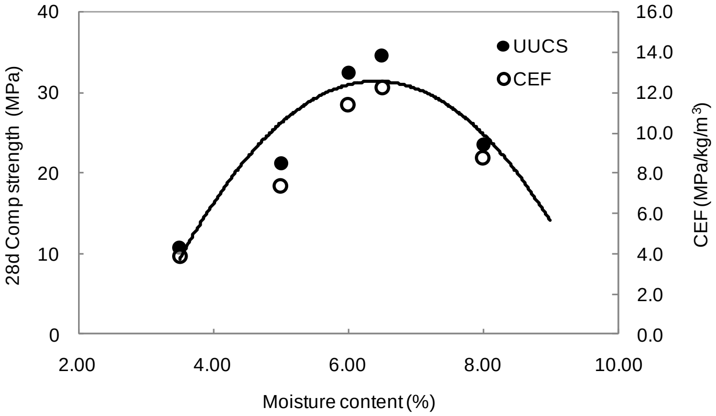


Figure 4-5 Compressive strength and CEF for non-admixed concretes

4.3 Admixed concrete

In this section, the results obtained from the experiments on admixed concretes for water reducers, AEA and DC products are presented. In order to simplify the presentation, many parameters are presented relative to the control mixture, while others are presented in as-measured quantities. For all the mixtures, the CSV was almost constant and hence a separate report is thus not presented. Water reducers available in the market have a retarding component and hence it is difficult to discuss retarders separately.

Water reduction is the amount of water reduced for obtaining same CSV as the control mixture at 15 min. For all the admixtures, the water reduction was observed. It should be noted that all the other properties are a consequence of the amount of water reduced by an admixture at a particular dosage. These properties cannot be seen as a standalone manifestation of the admixture dosage. The effectiveness of an admixture to alter the properties changes with water reduction even at the same dosage. For example, consider an admixture dosage of 1% used in two different mixtures, the first having a water reduction of 8% and the second having a water reduction of 12%. Consequently, the consistency and other properties will change although the admixture dosage appears to be the same. The relative cohesion and workability indices are obtained by dividing test value for admixed concrete mixture by the test value by that of the control mixture.

4.3.1 Water reducers

This section includes results and brief discussions on the relative properties of various types of water reducers and retarding water reducers. The distinction between plasticizers and superplasticizers can be made based on the water reduction achieved at various dosages.

Product P-05: PC based water reducer

Figure 4-6 shows the relative properties for this admixture at various dosages. The dosages ranged between 0% (control) and 3% (highest). It can be seen that the strength increases as the dosage increases, reaches a peak and then decreases.

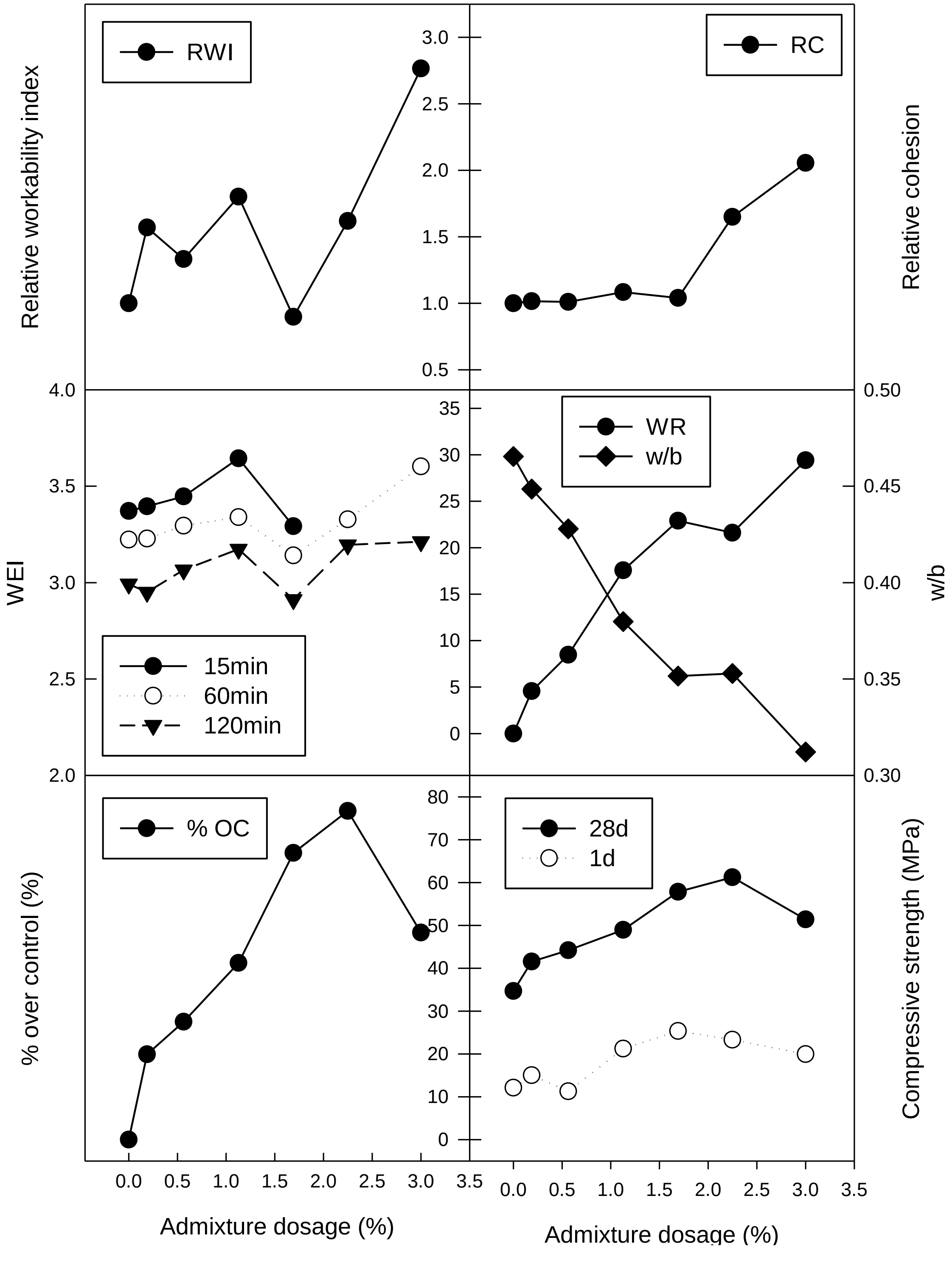


Figure 4-6. Relative properties for P-05 admixed concrete mixtures. RWI: Relative workability index; RC: Relative cohesion; %OC: % over control

The decrease is due to the water contributed by the admixture. The water reduction ranged between 0-30% and the corresponding w/b ratios are shown in the plot. The relative cohesion remains constant, but it actually increases, since the w/b ratio is decreasing with increasing dosage. After a certain dosage (2.25%), the cohesion increases dramatically making concrete extremely cohesive, this could be difficult to work with. Similar trend is observed for work index. The compactibility indices therefore could not be obtained for these dosages at 15 min. This admixture shows good retention of compactibility as can be seen from the relative trends at 60 and 120 min.

Product P-06: Ligno-PC based water reducer

Figure 4-7 shows the relative properties for this admixture at various dosages. The dosages ranged between 0% (control) and 3% (highest). The strength behavior is similar to the PC based product; however, the point of maximum increase in strength arrives relatively at an earlier dosage. This may be due to the presence of ligno-based component, which has a retarding tendency. The water reduction ranged between 0-24% with relative lesser water reduction than the PC-based product. The relative cohesion remains similar to control mixture with increasing water reduction; however, after an inflection point shows a reduction. Similar trend is observed for work index, which after showing initial increase attends a constant value. This admixture shows good retention of compactibility as can be seen from the relative trends in compactibilities at 60 and 120 min. The strength increase is relatively smaller than the corresponding dosages for the PC-based product.

Product P-10: Ligno based water reducer

Figure 4-8 shows the relative properties for this admixture at various dosages. The dosages ranged between 0% (control) and 3% (highest). Although relatively lesser, the strength behavior is similar to the PC based product, with the point of maximum increase reached at 2.25% dosage. The water reduction ranged between 0-20% with relative lesser water reduction than the PC-based and Ligno-PC based products. Initially, the relative cohesion remains similar to control mixture but with increasing water reduction shows a gradual reduction. Similar trend is observed for work index, which shows a gently reducing trend. This admixture shows excellent retention of compactibility as can be seen from the relative trends in compactibilities at 60 and 120 min. The retention is comparable to Ligno-PC based product. The strength increase is relatively smaller than the corresponding dosages for the PC-based and Ligno-PC based products. A caution to be exercised with ligno-based product is to check the finishibility of concrete, which may be relatively poor.

Product P-11: Retarding water reducer

This is a retarding water reducer and hence the dosage of admixture was restricted to 1.5% maximum. A trial at higher than this dosage lead to failure. Figure 4-9 shows the relative properties for this admixture at various dosages. At lower dosage, the strength showed a slight reduction, this might be due to the use of that dosage (@ 0.19%) without any water reduction. Strength increase is relatively poor at early ages and some of these mixtures showed lower than the control concrete strength. This may be due to the presence of ligno-based component, which has a retarding tendency. The water reduction ranged between 0-14%. The relative cohesion remains similar to control mixture with increasing water reduction. Relative work index however shows a decreasing trend initially and then shows an increase. This admixture shows better than P-05 and P-06 retention of compactibility as can be seen from the relative trends in compactibilities at 60 and 120 min.

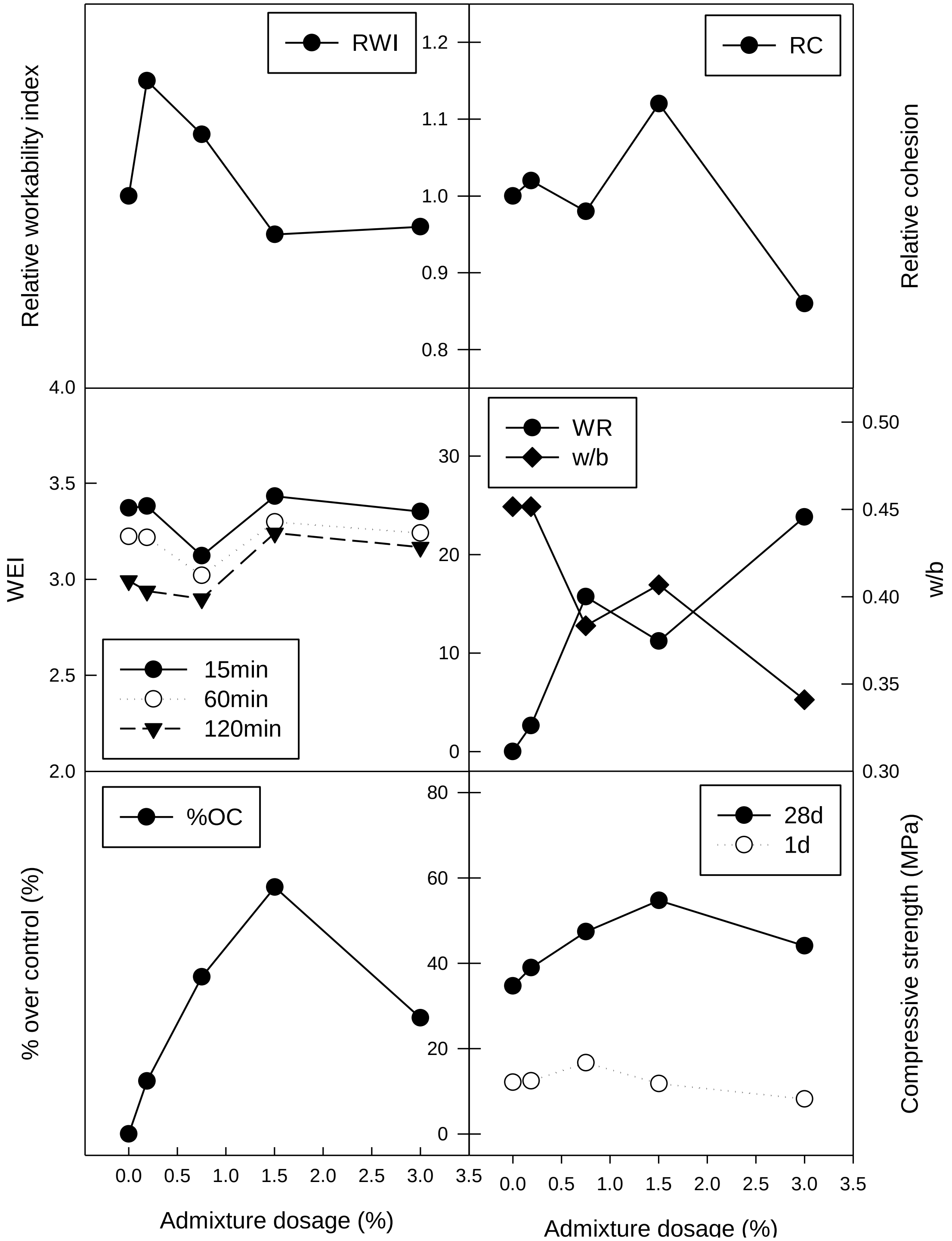


Figure 4-7. Relative properties of P-06 admixed concrete mixtures

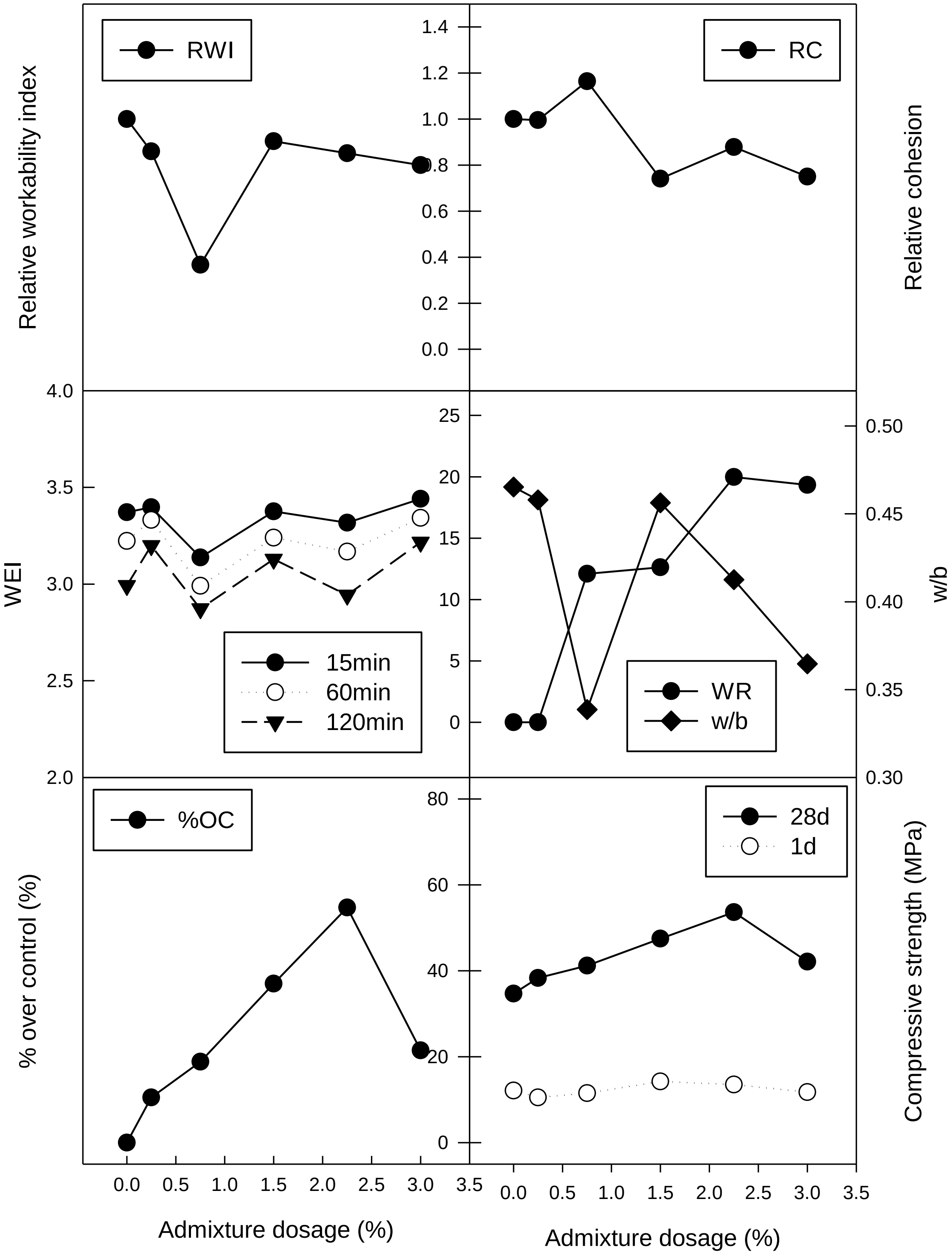


Figure 4-8. Relative properties of P-10 admixed concrete

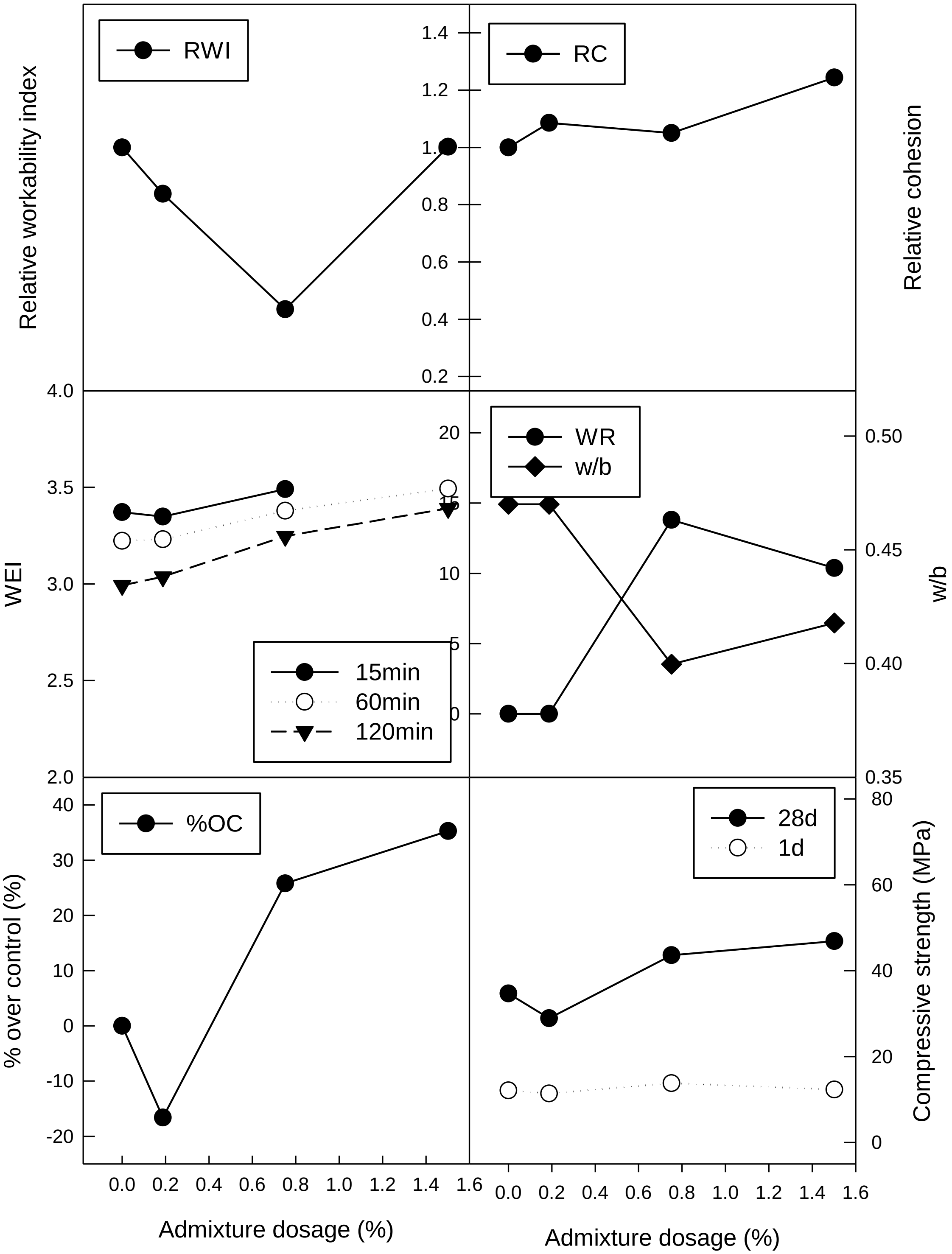


Figure 4-9. Relative properties of P-11 admixed concrete mixtures

Product P-13: Retarding water reducer

This is primarily a retarder and hence the dosage of admixture was restricted to 1.2% maximum. Figure 4-10 shows the relative properties for this admixture at various dosages.

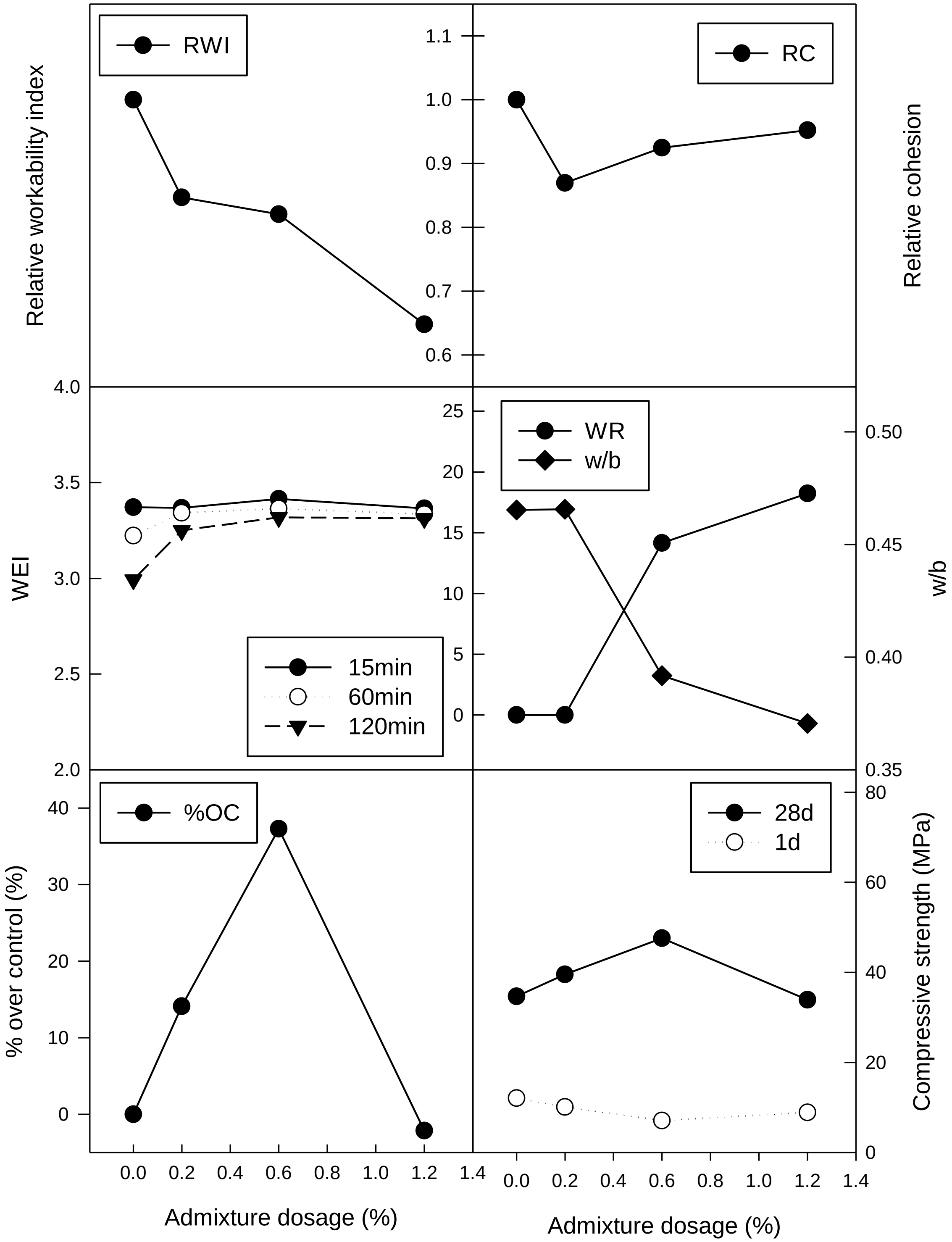


Figure 4-10. Relative properties of P-13 admixed concrete mixtures

There is in fact no relative strength gain at early ages; however, the strength picks up at the latter ages. This may be due to the presence of strong retarding component present in the admixture. The water reduction ranged between 0-18%. The relative cohesion shows a slightly decreasing trend. Relative work index however shows a continuously decreasing trend. This admixture shows the best retardation, which can be observed from the compactibility trends.

4.3.2 Air entraining admixtures

The primary objective of testing AEA’s was to study the influence of AEA’s on the fresh properties of RCC. Three products are reported here.

Product P-19 (Synthetic detergent based AEA)

Figure 4-11 shows the relative properties for this admixture at various dosages. The dosage ranged between 0 and 0.7%. The corresponding water reduction ranged between 0 and 23%. The relative cohesion shows an initial increase followed by a decreasing trend, while the work index shows a continually decreasing trend. It is possible to entrain substantial amount of air (up to 11%) using this type of AEA. As was expected, due to lack of a retarding component in this admixture, there was no retention of compactibility over the first two hours. It is interesting to note that it was difficult to determine the initial compactibility due to oozing out of water from the compacted sample under pressure. Initially the strength increases, reaches a peak and then decreases. The increase in strength is primarily due to water reduction.

Product P-20, Product 21

Product P-20 is a water-soluble hydrocarbon based product while P-21 is a modified resin. The relative properties are shown in Figures 4-12 and 4-13. The compactibility properties were not obtained because the AEA’s do not have any retarding component at the dosage ranges tested. An important thing to note is that the synthetic detergent based AEA is most effective in entraining air in fresh RCC.

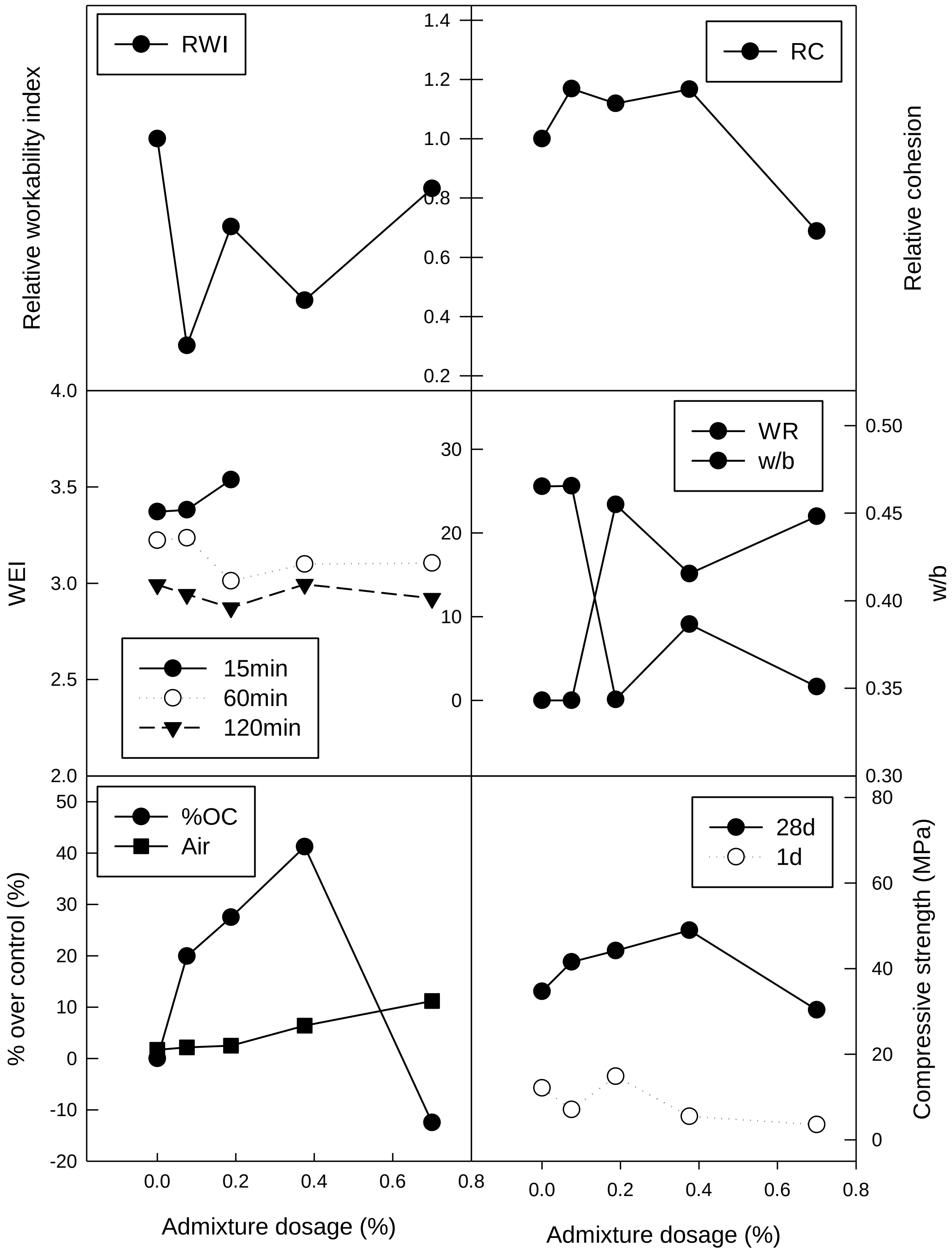


Figure 4-11. Relative properties of P-19 admixed concrete mixtures

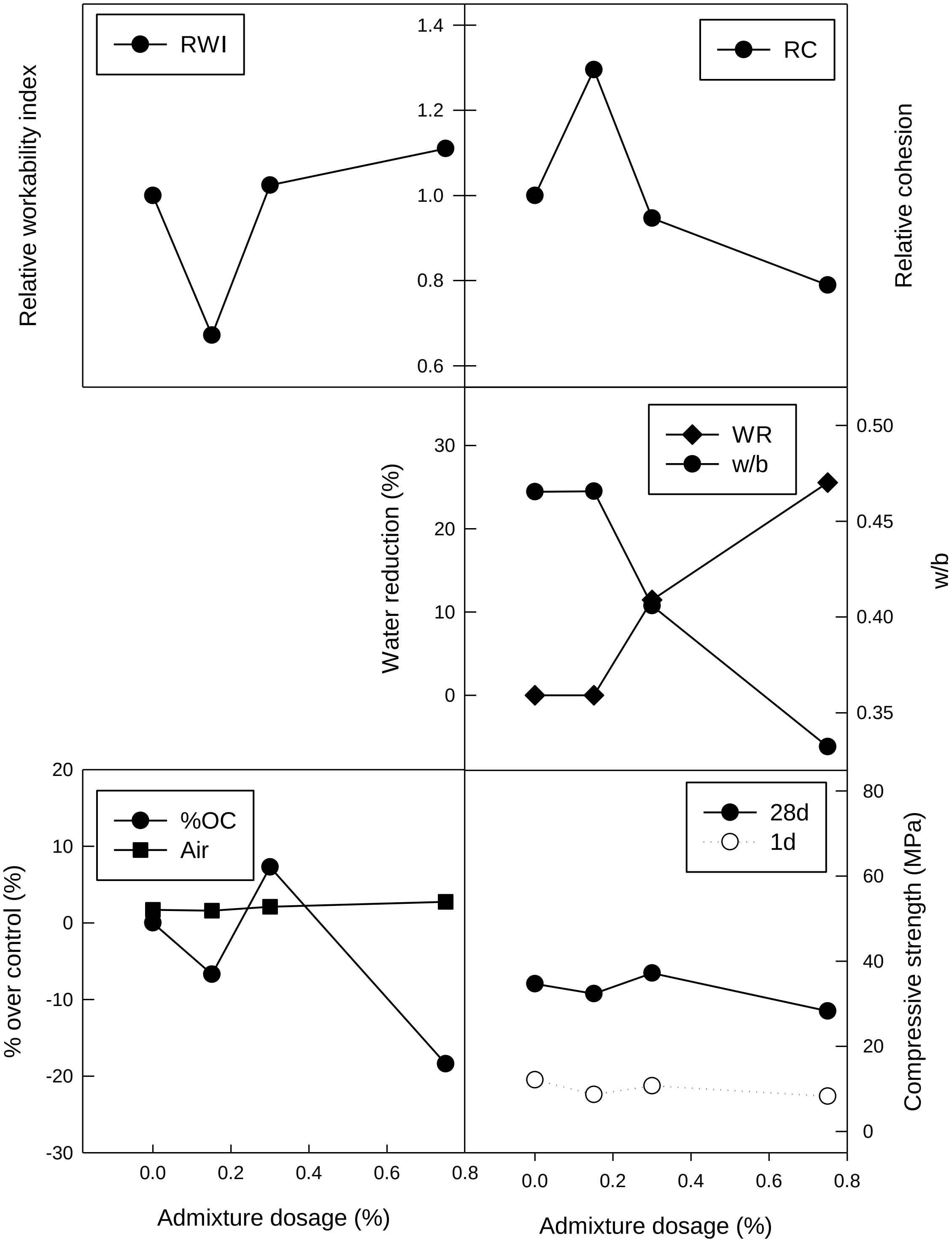


Figure 4-12. Relative properties of P-20 admixed concrete mixtures

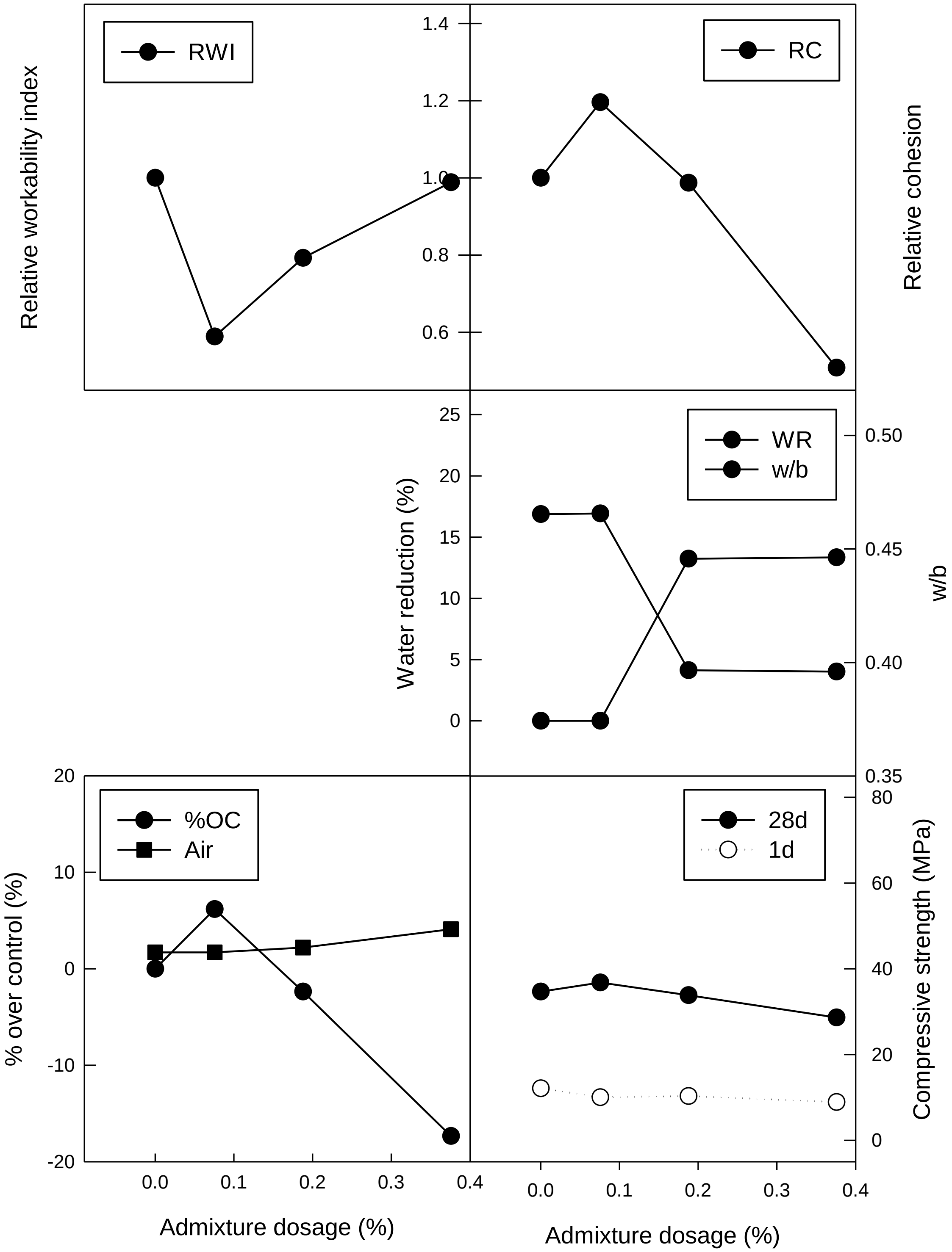


Figure 4-13. Relative properties of P-21 admixed concrete mixtures

4.3.3 Dry cast products

The dry cast (DC) products were tested because they are used in drier concretes and it was anticipated that the properties of RCC could similarly be influenced. Results from two types of DC products viz. surfactant based (P-28) and a polycarboxylate based (P-29) are reported here.

Product P-28: Surfactant based DC product

Refer to Figure 4-14 for trends. This is a surfactant based DC product tested over a dosage range of 0-1.5%. The corresponding water reductions ranged between 0-21%. The surface finish can significantly be improved by the use of this admixture. The relative cohesion improves slightly over control and remains more of less same, while the work index decreased slightly over the tested dosage range. The retention of workability was rather poor. The initial strength did not improve much, while the later strength showed a small increase.

Product P-29: PC based DC product

Refer to Figure 4-14 for trends. This is a PC based DC product tested over a dosage range of 0-2%. The corresponding water reductions ranged between 0-34%. The relative cohesion improves slightly over control and shows a decreasing trend subsequently; while the work index decreases with increasing dosage. The retention of workability was rather poor. The strength in general showed a decreasing trend in general.

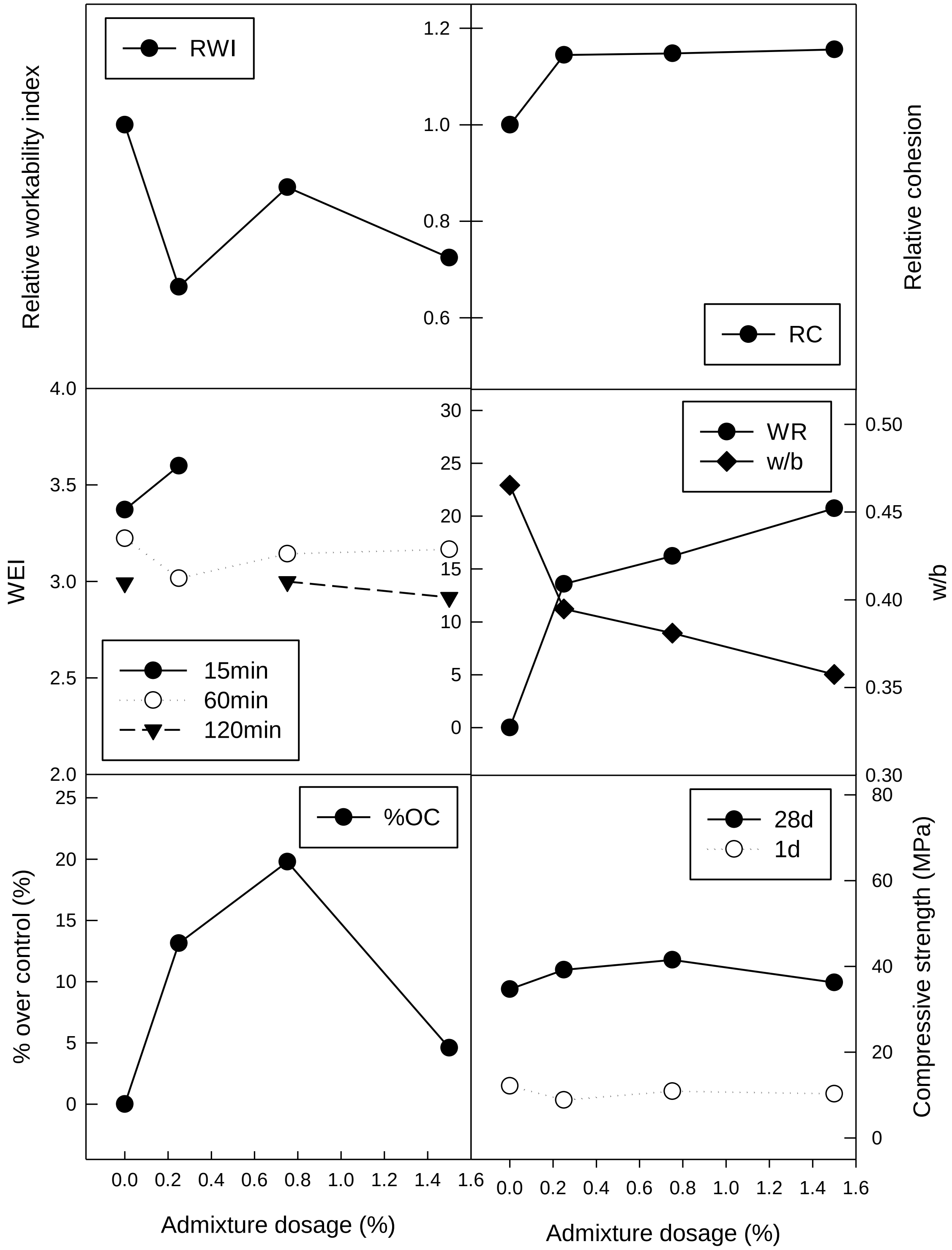


Figure 4-14. Relative properties of P-28 admixed concrete mixtures

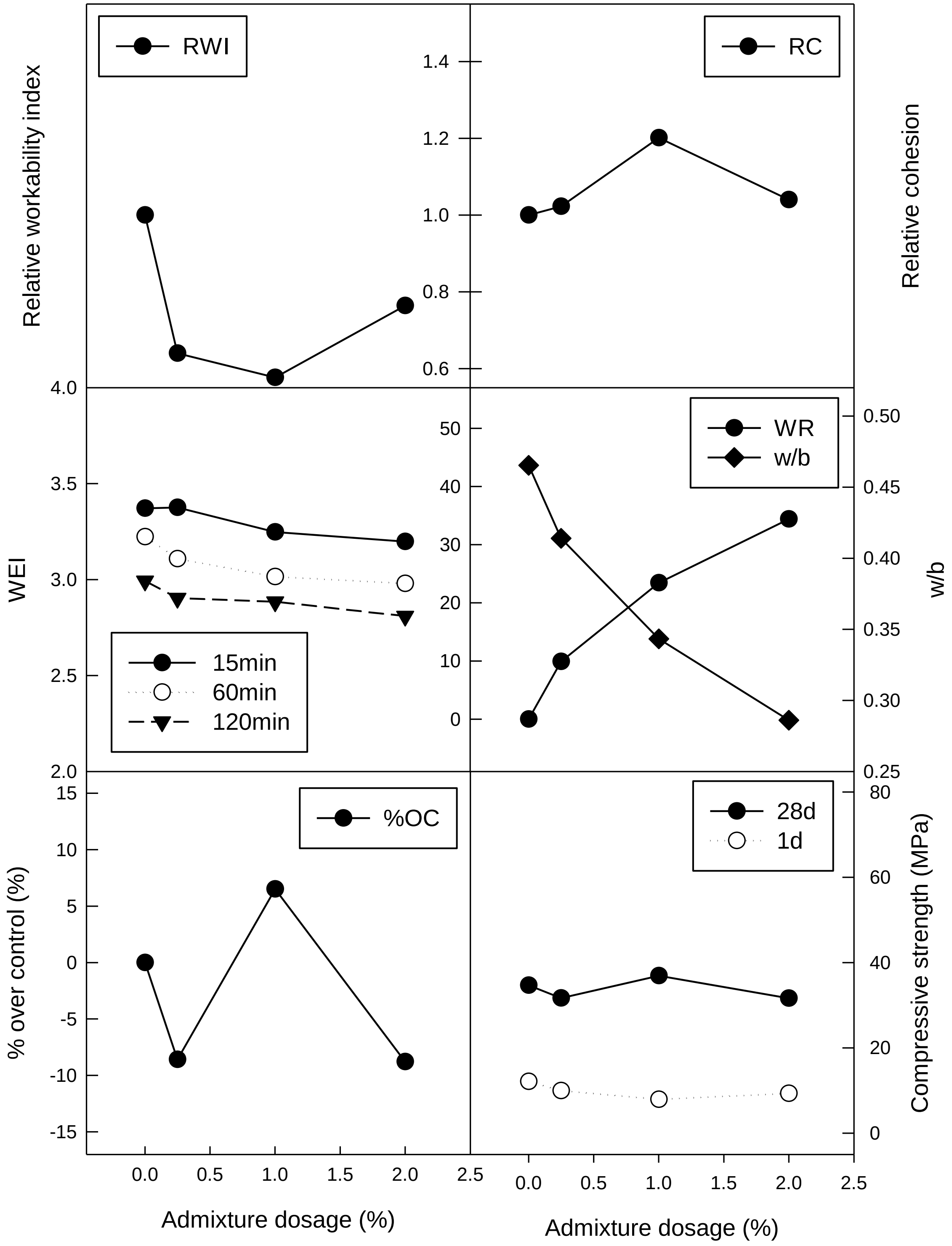


Figure 4-15. Relative properties of P-29 admixed concrete mixtures

4.4 Concluding remarks

The manufacturer recommended dosage is usually for normal concretes and hence cannot be used for RCC. It should be noted that the properties reported above are a function of the w/b ratio, which in turn decides the quantity and quality of the paste available for the admixtures to react with. The individual performances of various admixtures are noted here; there could be additional benefits obtained by using blends of admixtures. The admixtures tested in this program are representative of the most widely available products. Specific testing would still be required for further utilization of other products.

The segregation resistance and finishibility were not tested. However, a general word of caution can be offered. Segregation will generally manifest if a balance between water reduction and cohesiveness is required for achieving a mixture less prone to segregating. It is also important to note that the nature of cohesiveness offered by an admixture will depend on its type and dosage. For example, a PC based product and SD-AEA can both offer cohesiveness, however the nature of cohesion offered by the PC-based product is distinctly different from the SD based AEA. A caution can also be offered for the Ligno based water reducer, which shows a segregating tendency. The finishibility again is a function of the w/b ratio and the quality of paste. In addition, the amount of paste that can be brought to the surface under a specific compaction effort decides the finishibility of concrete. For the tested admixtures, the SD-based AEA leads to best finishibility followed by the PC-based product. The other two AEA’s do not improve finishibility much.

5. SUMMARY AND INFERENCES

This discussion excludes the cost considerations of different admixtures. It should also be taken into account that this is a lab study and will need field trials for its substantiation. Achieving the specified strength is usually not a concern in RCC mixtures; however, a careful choice of admixtures is required for obtaining the right blend of components of workability. For example, a high water reduction may be able to render an initially well-appearing and balanced mixture, but if there is no retardation of hydration reaction, then this balance may be lost. Similarly having good compactibility does not guarantee that the mixture is cohesive and vice-versa.

5.1 Admixture selection criteria

It is important to recognize what admixtures work best under a given set of conditions. Based on the results and perspectives on this work, Table 5-1 offers a guide to selection of admixtures to solve typical problems with RCC production and construction. While reading each attribute horizontally, the signs should be read for comparison. For example, consider the savings in the cement line, the potential of cement savings are highest with a PC-based admixture, followed by the Ligno-based and Ligno-PC blend. A retarding water reducer is less desirable since it tends to reduce the early strength. Using a SD-AEA will in fact reduce strength, if the balance between water reduction and air entrainment is not properly achieved, hence three negative signs. Admixtures like surfactant based DC products would tend not to affect the cement savings much.

One of the key themes emerging is the need to improve RCC compactibility so that it can be paver compacted. This is anticipated to reduce the compaction cost, while improving the product finish at the same time. This research has opened avenues for such investigations. Achieving uniform compaction along the depth of a pavement layer is an inherent issue in compacted layers, with RCC being no exception. Use of some of these admixtures can actually improve the uniformity of compaction in RCC. This is anticipated to be achieved by proper mixture formulation and appropriate admixture selection. In addition to this, this research also revealed that some of these admixtures have the potential to improve finishibility.

In essence it is the overall behavior of an admixture that is important than just improving one property or the other. The overall improvement means achieving a balance between cohesion, segregation resistance, compactibility, finishibility, and strength gain. while being cost effective and offering a cost-effective solution.

Table 5-1. Guide to admixture type selection

Condition/ stage	Details	Admixture type						
		PC-based	Ligno-based	PC-Ligno blend	Retarder	SD-AEA	Surfactant-DC	PC-based DC
Weather	Cold weather concreting	++	---	+	---	x	~	+
	Average/hot weather concreting	++	+++	++	+++	x	~	~
Materials	Savings in cement	+++	++	++	+	--	~	+
	Use of SCM's	++	--	+	---	~	~	++
	Poorly graded aggregate	++	-	+	-	++	+	++
	Coarser fine aggregate	+				++	++	+
	Very fine fine aggregate	-	++	+	+	--	+	
Mixing	Batch type	+	++	++	++	++	++	+
	Continuous flow type/pug mill	--	+			++	++	--
	Transit trucks	---	++	++	++	++	++	---
	Segregation issues	++	+ or -	+	+	++	++	++
Transportation	Water losses during transportation	+	+++	+	++	---	---	+
	Extended lead time	+	+++	+	++	---	---	+
Paving	High speed paving	+	++	++	++	--	--	+
	Average paving speed	++	++	++	++	++	++	++
Compaction	Reduce compaction cost	+++	++	++	+			++
	Extend compaction time window	+	+++	++	+++	---	---	+
Miscellaneous	Improve finishibility	++	~	+	~	+++	++	++
	Early opening to traffic	+++	+	++	-	-	+	++

5.2 General recommendations

For each admixture, the comments are offered with the condition that the same materials are mixed under similar conditions (mixer type, batching, mixing time). The recommendations include the possible avenues for applying each of these admixtures and some of the primary cautions to be exercised.

5.2.1 PC based water reducers

- At lower and intermediate dosages, these admixtures offer excellent overall performance. At higher dosages, there are concerns that need to be carefully addressed.
- These admixtures have an excellent potential for saving cement and/or binder.
- The finishibility of the concrete mixture improves.
- The admixture may require longer than normal time to start its activity. As such, the concrete may appear very stiff initially, but after some time (say 15 min or so), the appearance of concrete could dramatically change. In addition, their use in pugmills needs care and pre-screening.
- Higher dosages lead to higher water reduction and strength gain; however, these may entrain excessive air into concrete and make the mixture excessively sticky. Excessive air

may not be a critical issue for RCC, although this should be assessed on a case-to-case basis. Presence of stickiness beyond a certain limit may not be something desirable and hence higher dosages should be carefully avoided.

- Care should also be exercised in assessing the setting behavior at various dosages.
- There are multiple formulations and families of PC-based admixtures available in the market. These could behave differently depending on their chemistry and hence detailed comparative investigations should be carried in lab before.
- RCC can be made paver compactable with the use of these admixtures.

5.2.2 Ligno-based water reducers

- This is one of the better admixtures from technical as well as economic perspectives. Higher dosages can delay the setting of concrete; hence, care should be exercised while using such dosages.
- These can be used in hot weathers. Their use in mixtures containing SCM should be limited and prior testing is essential. In cold weathers, these admixtures could cause setting delays and poor strength gain.
- The compaction window can be extended as a function of the dosage and water reduction.
- The finishibility of concrete could be a concern, as this admixture has not shown any improvement in the finishibility.

5.2.3 Ligno-PC based water reducers

- These admixtures offer the advantages of both ligno- and PC-based water reducers and hence are a good intermediate solution.
- Care should be exercised in selecting the right product with adequate water reduction, improvement in cohesion, workability and finishibility and sufficient setting time. This has to be balanced with economic considerations.

5.2.4 Synthetic detergent based AEA

- These are highly water sensitive admixtures. A slight change in the water content could lead to dramatic changes in the entrained air content. Hence, the moisture contents of the aggregates should be monitored with extra care while using these AEA’s.
- Similarly, it is important to have the batching plant well calibrated so that the dosing is controlled. Negative batching tolerances will not affect the mixture performance as much as the positive tolerances could.
- Variations in the dosages could lead to some drastic changes in the workability of concrete mixtures.

- Sole use of AEA could be permitted, provided a balance between the water reduction, air entrainment, workability and strength is tested in the lab. Else, it is recommended to use a retarding water reducer for retaining the compactibility of concrete.

Other AEA types can be used with prior testing and evaluation as outlined in this work.

5.2.5 DC products

- The DC products are good solution for RCC, provided they offer adequate retardation.
- The surfactant-based product offers significant improvement in finishibility while not entraining excessive air in the mixture. There is no significant strength gain with its use; however, the workability improvement is significant. This product may turn out to be a cost effective solution.
- The PC-based product offers somewhat comparable advantages to that of PC-based water reducer. The strength gain is however not so significant, and this can be attributed to the relatively weak action of this admixture. Sufficient workability improvement can be achieved with good retention. This type of product may be a good alternative to PC-based water reducers, which are expensive.

5.3 Concluding remarks and recommendations

This work has developed some test methods for characterizing the fresh properties of RCC. These include methods for consistency, compactibility, shearing resistance and cohesion. All these methods have good discriminating power and are recommended for field use. Further fine-tuning of some of these methods may be necessary to adopt these better for RCC. For example, the gyratory compactor needs to have the ability of reducing the confining pressure below 200 kPa. There is a need to standardize these test methods and accommodate them into ASTM and other standards.

The applicability of different chemical admixtures was evaluated through lab testing. It is observed that different admixtures can enhance different aspects of fresh RCC. The use of these admixtures can also help improve mixer efficiency, especially that of pugmills and transit trucks. Water reducers can save the cement costs greatly and because of significant reduction in the water/binder ratio enhance the durability and life of the pavement. Air entrainment is possible, if the admixture chemistry is properly selected. This in-turn means that RCC can be made more freeze-thaw durable. The dry cast products are helpful in improving some of the fresh properties, while offering a less expensive admixture solution.

Finally, this work reports the results of solitary admixtures. Each of these has its own strengths and weaknesses. Combining admixtures to complement each others' functionalities seems to be the next step in evaluating these admixtures further. Moreover, with this work capturing the attention of the admixture manufacturers, which amalgamated to the growing interest in RCC, could lead to further research and development in admixture formulations to better suit the needs of RCC industry.

REFERENCES

ACI Committee 116, A. C. (2000). Cement and Concrete Technology. Farmington Hills, MI, USA, American Concrete Institute.

ACI Committee 325 (1995). *State-of-the-art report on roller-compacted concrete pavements*. Detroit, Mich., American Concrete Institute.

Aïtcin, P.-C. (2008). *Binders for durable and sustainable concrete*. London ; New York, Taylor & Francis.

Alexandridis, A. and N. J. Gardner (1981). "Mechanical behaviour of fresh concrete." *Cement and Concrete Research***. 11**(3): 323-339.

Amer, N. H. (2002). Development and validation of a new test method for fabricating RCC specimens, University of Alabama at Birmingham 2002.**:** xiii, 121 leaves.

ASTM (2006). ASTM C260 - 06 Standard Specification for Air-Entraining Admixtures for Concrete. West Conshohocken, PA, USA, ASTM International**:** 3.

ASTM (2008). ASTM C33 / C33M - 08 Standard Specification for Concrete Aggregates. West Conshohocken, PA, USA, ASTM International**:** 11.

ASTM (2008). ASTM C494 / C494M - 08a Standard Specification for Chemical Admixtures for Concrete. West Conshohocken, PA, USA, ASTM International**:** 10.

ASTM (2008). ASTM C1170 / C1170M - 08 Standard Test Method for Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table. West Conshohocken, PA, USA, ASTM International**:** 10.

ASTM (2009). ASTM C231 / C231M - 09b Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method. West Conshohocken, PA, USA, ASTM International**:** 10.

Bartos, P. J. M., M. Sonebi, et al., Eds. (2002). *Workability and rheology of fresh concrete: Compendium of tests*. Cachan Cedex, France, RILEM.

Bureau of Indian Standards (1959). IS1199 (1959) Methods of sampling and analysis of concrete. India, Bureau of Indian Standards.

Cabrera, J. G. and C. D. Atis (1999). *Design and properties of high volume fly ash high performance concrete*. Second CANMET/ACI International conference on High performance concrete and performance and quality of concrete structures, Gramado, RS, Brazil.

Cabrera, J. G. and R. E. Lee (1985). *A new method for the measurement of workability of high pulverised fuel ash concrete*. 7th International Ash utilization symposium, Orlando, Florida, USA, National ash association.

Christensen, B., J. and H. Farzam (2006). Chemical admixtures. *Significance of tests and properties of concrete and concrete making materials*. J. F. Lamond and J. H. Pielert. West Conshohocken, PA, USA, ASTM International**:** 484-494.

Collepardi, M. (1995). Water reducers/retarders. *Concrete admixtures handbook*. V. S. Ramachandran. New Jersey, Noyes**:** 286-409.

Dodson, V. H. (1990). *Concrete admixtures*. New York, Van Nostrand Reinhold.

Dransfield, J. (2003). Admixtures for concrete, mortar and grout. *Advanced concrete technology, Constituent materials*. J. a. C. Newman, Ban Seng. Burlington, MA, Butterworth-Heinemann**:** 4/1-4/36.

Dransfield, J. (2006). "Admixture sheet - ATS 1 Normal plasticizing / water reducing." from www.admixtures.org.uk.

Dransfield, J. (2006) "Admixture sheet - ATS 5 Concrete air-entraining admixtures." 4.

Dransfield, J. (2006) "Admixture technical sheet-ATS 2 Superplasticizing/High range water reducing." 5p.

Du, L. and K. J. Folliard (2005). "Mechanisms of air entrainment in concrete." *Cement and Concrete Research***.** **35**(8): 1463-1471.

Edmeades, R., M. and P. Hewlett, C. (1998). Cement admixtures. *Lea's chemistry of cement and concrete*. P. C. Hewlett. London, UK, Arnold**:** 837-902.

Hansen, K. D. and W. G. Reinhardt (1991). *Roller-compacted concrete dams*. New York, McGraw-Hill.

Hazaree, C. V. (2007). Transport properties and freeze-thaw resistance of roller compacted concrete (RCC) for pavement applications. Ames, Iowa, Iowa State University.

Hazaree, C. V., Wang, K.W. and Ceylan, H. (2006). Optimizing mix proportions for durable Roller compacted concrete in Indian conditions.”. Proc.-Airfield and Highway Pavement: Meeting Today’s Challenges with Emerging Technologies. I. L. Al-Qadi. Atlanta, GA, USA, ASCE, Reston, VA, USA**:** 543-556.

IS: 1199 (1959) (1959). IS1199 (1959) Methods of sampling and analysis of concrete. India, Bureau of Indian Standards.

Juvas, K. (1987). Workability tests with stiff concretes. Parainen, Finland, Partek concrete laboratory report**:** 10.

Juvas, K. (1994). *Very dry precasting concrete*. Special concretes: workability and mixing, Paisley, Scotland, RILEM.

Juvas, K. J. (1990). *Experiences in measuring rheological properties of concrete having workability from high-slump to low-slump*. RILEM Colloquim on properties of fresh concrete, Hanover, West Germany, Chapman and Hall.

Juvas, K. J. (1996). Very dry precasting concretes. *Production methods and workability of concrete*. P. J. M. Bartos, D. L. Marrs and D. J. Cleland. London, UK, E&FN Spon**:** 125-140.

Kappi, A. and E. Nordenswan (2007). Workability of no-slump concrete. Concrete International. USA, ACI. **29 (3):** 37-41.

Kokubu, K., J. G. Cabrera, et al. (1996). "Compaction properties of roller compacted concrete." *Cement and Cocnrete Composites*. **18**(2): 109-117.

L'Hermite, R. (1949). "La rheologies du beton frais et la vibration (The rheology of fresh concrete and vibration)." *Revue des Materiaux de construction*. **405**: 179.

Lambe, T. W. and R. V. Whitman (1969). *Soil mechanics*. New York,, Wiley.

Li, Z. (2007). "State of workability design technology for fresh concrete in Japan." *Cement and Concrete Research***.** **37**(9): 1308-1320.

Neville, A. M. (1973). *Summary*. RILEM seminar on Fresh concrete: Important properties and their measurements, Leeds, England, Department of civil engineering, University of Leeds.

Neville, A. M. (1995). *Properties of concrete*. Harlow, Longman Group.

Paakkinen, I. (1986). Intensive compaction tester devide for testing the compactibility of no-slump concrete. *Nordic concrete research report No.5***:** 109-116.

Pittman and Anderton (2009), “The use of roller-compacted concrete (RCC) pavements in the United States,” Sixth International Conference on Maintenance and Rehabilitation of Pavements and Technological Control (MAIRE PAV 6), July 8-10, 2009, Torino, Italy, pp. 419-429. (http://www.mairepav6.it/uk/

Popovics, S. (1982). "Fundamentals of Portland cement concrete--a quantitative approach."

Powers, T. C. (1968). *The properties of fresh concrete*. New York, Wiley.

Ramachandran, V. S. and Knovel (Firm). (1995). "Concrete admixtures handbook : properties, science, and technology." *Building materials science series*. 2nd. from Access to the Knovel online version restricted; authentication may be required: http://www.knovel.com/knovel2/Toc.jsp?BookID=365.

Ramachandran, V. S. and V. M. Malhotra (1995). Superplasticizers. *Concrete admixtures handbook*. V. S. Ramachandran. Park Ridge, NJ, USA, Noyes publications**:** 410-517.

Ritchie, A., G.B., (1968). "The rheology of fresh concrete." Proc. ASCE **94**: 55-74.

Rixom, R. a. M., N. (1999). *Chemical Admixtures for Concrete*. London, UK, E&FN SPON.

Service d'Expertise en Matériaux Inc. (2004). *Frost durability of roller-compacted concrete pavements*. Skokie, Ill., Portland Cement Association.

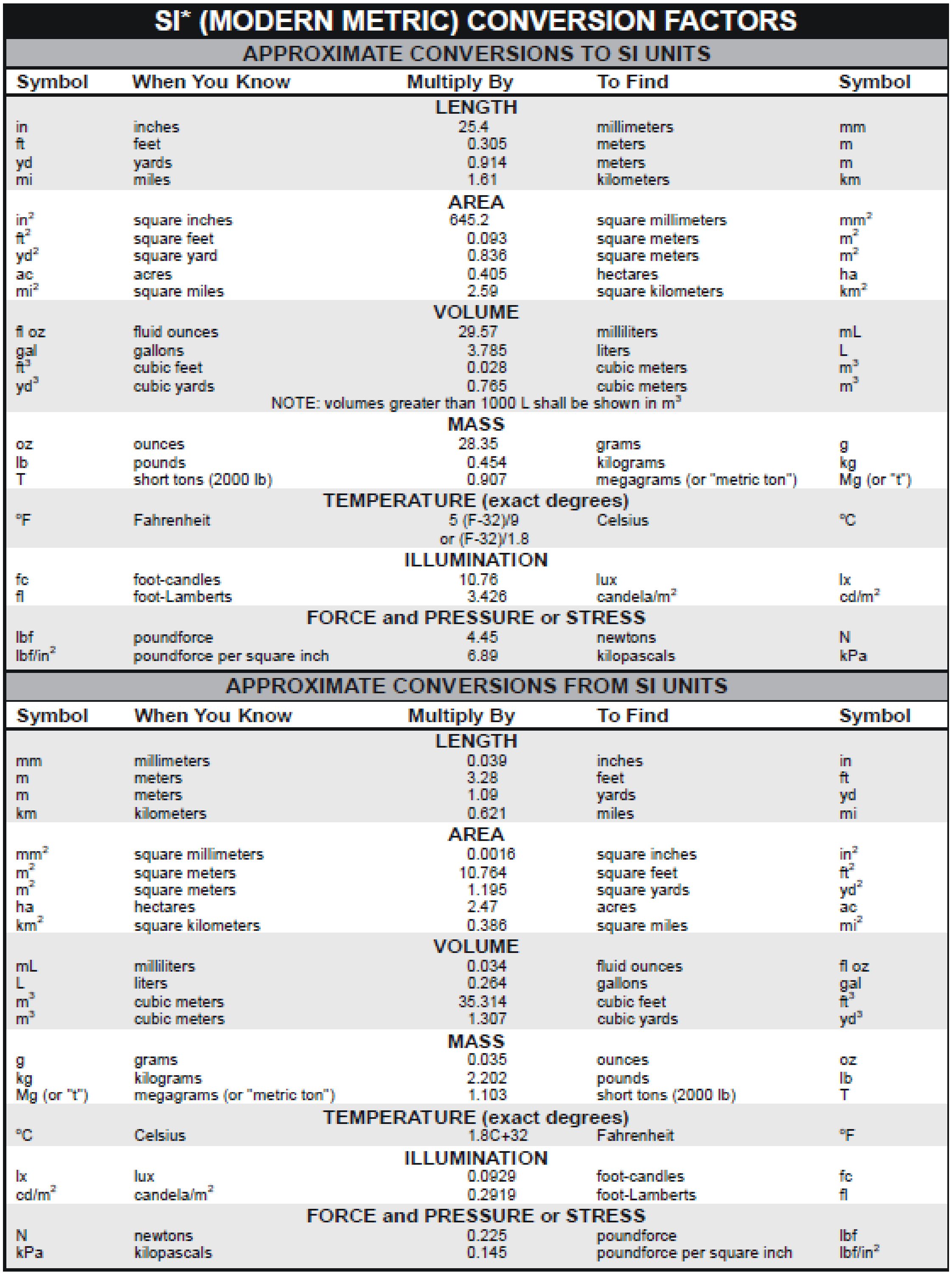
Tassios, P. T. (1973). *Plasticity and cohesiveness of fresh concrete*. RILEM seminar on fresh concrete: Important properties and their measurement, Leeds, England, Department of Civil engineering, University of Leeds.

Vikan, H., Justnes, H., Winnefeld, F. and Figi, R. (2007). Correlating Cement Characteristics with Rheology of Paste. *Cement and Concrete Research*. **37:** 1502-1511.

APPENDIX A: PHYSICAL PROPERTIES AND COMPOSITION OF BINDERS

Description	Units and test standard	C2	F1
		Type I	Class F
Physical			
Fineness by Air Permeability	*(m^2/kg; C204-07)*	384.3	NA
Fineness by 45 um (No. 325) Sieve	*(% passing; C430-08)*	91.8	80.55
Compressive Strength	*(C109/C109M-08)*		
1-day	(MPa)	16.5	NA
3-day	(MPa)	25.2	NA
7-day	(MPa)	30.9	NA
28-day	(MPa)	40.9	NA
Time of Set, Vicat	*(initial, min.; C191-08)*	79.7	NA
Air Content of Mortar	*(%; C185-08)*	7.00	NA
Autoclave Expansion	*(%; C151/C151M-09)*	0.03	-0.01
Sulfate Expansion	*(%; C1038-04)*	0.0	NA
Specific Gravity	*(%; C188-95)*	3.150	2.36
Water required	*(% of control)*	NA	95.5
Strength activity index w/ OPC	*(C311-00)*		
at 7d	*(% of control)*	NA	80.1
at 28d	*(% of control)*	NA	88.4
Chemical			
Silica Dioxide	(SiO_2; C114-09)	20.4	54.1
Aluminum Oxide	(Al_2O_3; C114-09)	4.3	23.7
Ferric Oxide	(Fe_2O_3; C114-09)	3.2	5.3
Calcium Oxide	(CaO; C114-09)	63.2	8.5
Magnesium Oxide	(MgO; C114-09)	3.0	2.4
Sulphur Trioxide	(SO_3; C114-09)	3.4	0.4
Loss on Ignition	(L.O.I.; C114-09)	1.1	0.6
Insoluble Residue	(C114-09)	0.2	NA
Free Lime	(f-CaO)	1.1	NA
Tricalcium Silicate	(C_3S; C150-07)	58.3	NA
Tricalcium Aluminate	(C_3A; C150-07)	6.0	NA
Equivalent alkalies	(NaEq, %)	0.5	1.3
% pozzolan addition rate	(%)	NA	NA

APPENDIX B: UNIT CONVERSION FACTORS



SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	$candela/m^2$	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	$candela/m^2$	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)