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Transport properties and freeze-thaw resistance of roller compacted concrete (RCC) for pavement applications

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Transport properties and freeze-thaw resistance of roller compacted concrete (RCC) for pavement applications

by

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LIST OF TERMS AND ABBREVIATIONS

CVC	Conventionally compacted concrete
Desorption ratio (Sat-OD)	is defined as the difference of densities at the saturated condition (samples drawn from the curing room) and the density at the end of oven drying for a period equivalent to preconditioning period divided by the saturated specimen density
Desorption ratio (Sat-Pre)	is defined as the difference of densities at the saturated condition (samples drawn from the curing room) and the density at the end of preconditioning divided by the saturated specimen density
Dryness ratio	is defined as the ratio of desorption ratio (Sat-Pre) and desorption ratio (Sat-OD)
F-T	Freeze/Thaw
ITZ	Interfacial transition zone
MDD	Maximum dry density
OMC	Optimum moisture content
QC/QA	Quality control/Quality assurance
RCC	Roller compacted concrete
SEM	Scanning electron microscope
UCS	Unconfined compressive strength
VBT	Ve-be time

LIST OF ORGANIZATIONS AND SOCIETIES

AASHTO	American association for state highways and transportation officials
ACI	American concrete Institute
ASCE	American society of civil engineers
ASTM	American society for testing and materials
BIS	Bureau of Indian standards
BSI	British standards institute
CCA	Cement, concrete and aggregates Australia
CCANZ	Cement and concrete association of New Zealand
CCI	Cement and concrete Institute, South Africa
CSCE	Canadian society of civil engineers
GSA	Geological society of America
JSCE	Japanese society for civil engineers
NIST	National institute for standards and technology

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ABSTRACT

This thesis reports a comprehensive laboratory study covering 12 roller compacted concrete (RCC) mixes for pavement applications. Apart from the experimentation part, an exclusive survey of the state-of-the-art on RCC is reported. Mixes with cement contents from 100 kg/m^3 to 450 kg/m^3 with and without air entraining admixtures were proportioned for studying a few of the mechanical and durability characteristics. Locally available olitic limestone was used as aggregates and the mix proportioning was done using soil-analogy method. Tests such as Ve-be time, moisture-density profiles, compressive strength, water absorption, permeable voids content, sorptivity and desorptivity and rapid Freeze-Thaw (F-T) resistance were performed. Scanning electron microscope (SEM) images and air void analyses of these mixes was also conducted to check the feasibility of entraining air in RCC.

It was observed that there exists optimum cement content at which maximum dry density is obtained, which in turn leads to optimization of other mechanical, bulk and durability characteristics. An improvisation in F-T behavior was observed when the mixes were entrained with air. Due to the exposed and fractured limestone, partially produced by sample preparation method, inherent heterogeneity of cement paste and internal cracking, the samples might have demonstrated poor F-T resistance. SEM analyses showed the presence of entrained air voids in the mixes indicating the possibility of entraining air.

Key words: RCC, Cement content, permeable voids, Sorptivity, desorptivity, Freeze-Thaw, SEM, Air void analysis

1. INTRODUCTION AND PROBLEM STATEMENT

Summary

This chapter briefs about the current state-of-research on Roller Compacted Concrete (RCC) and describes the reasons for the lack of know-how limiting its applications. Further to this, it states some of the drawbacks of using RCC and identifies the probable reasons for poor understanding of the subject matter. Recognizing the deficiency in the body-of-knowledge on the water capillarity as the missing link connecting durability of RCC to its performance, this chapter lays down the foundation for the work in terms of the research need statement.

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1.1 Context and Motivation

Sustainable development in civil engineering is driving engineers to either look for newer materials or modify existing ones in a sustainable way. Durability concerns of various forms and magnitude are getting addressed in multitudes of ways. Roller compacted concrete (RCC), a construction technology and construction material, which, due to incomplete exploration and meager research efforts is lagging wide scale applications. Primary reasons for this being some of the un-rectified drawbacks in RCC like the finishibility, riding quality, etc, which when combined with the limited and slow mechanics of moving this further and applying this technology more aggressively is significantly limiting its expansion. Research in recent years and acceptance of this material and technology has now started uncovering its positive aspects. Moreover the multiplicity of its applications worldwide is helping this process evolve in a more generic yet standardized way.

RCC has well established advantages in its hydraulic engineering applications and its merits are getting recognized even in the pavement engineering. As a material, RCC offers cost savings in terms of materials' costs, width of application of different types of materials, production, transportation and placement speeds. In addition to this there are core benefits to the management in terms of increased construction speed and saving of dollars due to higher placement rates, lower man hours and lesser machinery requirements. Due to the flexibility that RCC provides in terms of its applications, it is becoming a material of choice.

One of the unsolved riddles in RCC technology is its inconsistent response to the Freeze-Thaw (F-T) loading in laboratory and field and the lack of well-defined connection between the two. Key reason for such a poor understanding of this material is its innate heterogeneous nature accompanied by the lack of depth of knowing of how the most dangerous process of water transport is taking place inside and within this material. Literature is full of such missing links but there is no work that tries to define and understand this missing link.

A need therefore exists for a study that clearly identifies the key water transport phenomenon in RCC. This could then be utilized in correlating it with the performance of RCC under hydro-thermal loading named as F-T. This work is therefore an attempt to understand some of the water transport phenomenon taking place in a very dry concrete called as RCC. For this an understanding of the transition from the usual nature of concrete to this very dry state-low consistency concrete needs to be carefully understood. In essence this material lies somewhere between clay bricks and the conventionally compacted concrete (CVC) as far as its water transport due to capillarity is concerned. The type of concrete that closely resembles this material is the one used for making concrete paving blocks. Hence for a better understanding of the nature of variation of considered characteristics, a wide range of cement contents covering all possible combinations needs to be studied. Laboratory studies of this extent more often than not tend to get application specific. Contrary to this, the current study will try to gather the width and the depth of the body of knowledge relevant to the subject matter.

1.2 Study Objectives

In order to achieve the pre-conceived objectives, this study was undertaken with the following objectives:

1. *Strength evolution with change in the cement factor/cement content:* This objective was defined in order to understand the variations that take place in the nature of strength evolution with the change in the cement factor. With increase in the cement factor different mixes respond differently to the mechanical loading. Strength in turn will influence other properties related to mechanical load bearing capacity and durability response of the material to environmental loadings. Usually, using this

relationship between the compressive strength and cement factor could provide engineers with an economical mix design and help specify concretes.

2. *Role of compaction voids in F-T resistance:* Compaction voids generated during the compaction of RCC have the potency to bear the hydro-thermal loading. Even though research till date has not fully substantiated this hypothesis, evidence from research and practice has revealed some hope. With gradual variation in the cement factors of the mixes, the nature of compaction voids will also change leading to differences in its response to the environmental loading. This objective will help understand the necessity of entraining air in RCC and the role of air entraining admixture.
3. *Nature of sorption and desorption behavior:* The water uptake of concrete is governed by the capillarity and porosity of the material. This in-turn will decide the time response of the material to get saturated and consequently its long-term water uptake. Similarly desorptivity will decide the ability of a material to drain out the water. This is crucial when the concrete thaws in the field. Eventually these two characteristics combined together will affect the F-T response of the material.
4. *Distribution of air voids:* It is important to understand how exactly the air voids are distributed inside the concrete structure, so that their role in F-T resistance could be identified.

For the intended objectives, this study covered a cement content range for all possible RCC-pavement applications starting from 100 kg/m^3 to 450 kg/m^3. Tests like measuring the consistency, optimizing moisture-density, compressive strength test, water absorption, permeable voids content, sorptivity and desorptivity were planned to be carried out. In addition to this, techniques like scanning electron were planned to be used for gathering relevant information for the air voids' contents of the mixtures, their nature and distribution and the cement paste.

1.3 Definitions of scope and limitations

This dissertation presents a state-of-the research on relevant topics. Included in the survey is the summary of benefits and drawbacks of using RCC. Subsequent to this, the mechanical properties of RCC are discussed. This is followed by an elaborate discussion on the durability characteristics (excluding F-T resistance) of RCC mixes. Succeeding this is a section that briefs about the water transportation phenomena along with an in-depth discussion on sorptivity and desorptivity of concrete materials. Finally the section on literature review concludes with the discussion on mix-proportioning strategies followed by the F-T resistance of RCC.

The laboratory experimental work begins with the identification of proper materials and test methods and is followed by the actual experimental work tests results and discussions on the same. Considering the timeline and available resources the following scope of work was defined as far as the experiments are concerned:

1. *Mixes shall cover a wide range of applications:* The range of cement contents would be from 100 kg/m^3 to 450 kg/m^3. Only Ordinary Portland cement (OPC) of ASTM Type I would be used. No supplementary cementitious materials shall be used in these series of investigations.
2. *Phases:* The complete experimental work shall be divided in two phases viz. Phase I and II. Phase-I shall consist of all the mixes in the above range of cement contents in steps of 50 kg/m^3. All the mixes in this phase shall be non air-entrained and shall incorporate water reducer in order to enhance the consistency and plasticity of the mixes. Phase II mixes shall consist of selected-comparative mixes to cover the entire range of cement content. All the mixes in this phase shall

be air-entrained and will incorporate the same quantities of water reducer in order to have a common basis of comparison between the two phases.

3. *Optimization:* Attempts shall be made only to optimize the dry density and moisture contents after the theoretical optimization of particle size distributions (PSD) of the aggregates. No attempts to optimize the compaction process shall be made. Thus a constant predefined compaction procedure shall be used in these investigations.
4. *Concrete Mixing:* The mixing procedure shall be pre-optimized taking cognizance of the available resources and shall not be altered thereafter. Laboratory drum mixer shall be utilized for all the mixing operations.
5. *Mechanical testing:* Compressive strengths shall be performed on cylindrical samples at the age of 7 and 28 days only. No further testing shall be done.
6. *Bulk properties:* Bulk properties like the water absorption, density and boiling or permeable voids shall be performed on properly extracted specimens. This behavior shall be defined for three different layers in concrete specimens viz. the top, middle and bottom. The sample extraction scheme and specimen sizes shall be defined during the course of study.
7. *Capillarity:* A complete evaluation of the available test methods on sorptivity measurement of concrete shall be done before selecting the final test methods. Tests similar to those for the bulk properties shall be extracted and used for the analyses. Similarly, desorptivity tests shall be predefined and then conducted according to this predefined procedure, since no standard exists for its test procedure.
8. *Cyclic F-T:* F-T tests shall be run at the end of 21 days after coring the samples without applying any coating and using freezing and thawing both in water

procedure. These tests shall be run until a drop of 60 % in the dynamic modulus measurement from the initially measured value is not observed.

9. *Scanning electron microscope (SEM) Analysis:* SEM analysis shall be carried out to analyze the air voids content and their distribution. This shall not be further extended to cover the higher compaction voids.

Analysis and discussions would follow the complete experimental program has been established and performed. Appropriate conclusions would then be drawn and reported in the form of concluding chapter along with the scope for future work in the areas related to the findings of this work.

1.4 Scheme of presentation

This section outlines the presentation of this thesis. Figure 1 shows the schematic sketch of the structure of the thesis.

Chapter 1 is dedicated to defining the problem statement and background of this work. Additionally, this chapter defines the objectives and scope of the presented work.

Chapter 2 is devoted to the extensive state-of-the-art research literature review carried out for this work. This includes the primary literature directly available on the subject matter and extended literature that covers the mechanics of water transport in concrete.

Chapter 3 describes the materials and methods used and the experiment in general. ***Chapter 4*** presents the results and discussions on the available sets of results.

Chapter 5 presents the general conclusions on the basis of this work along with covers the scope for future work.

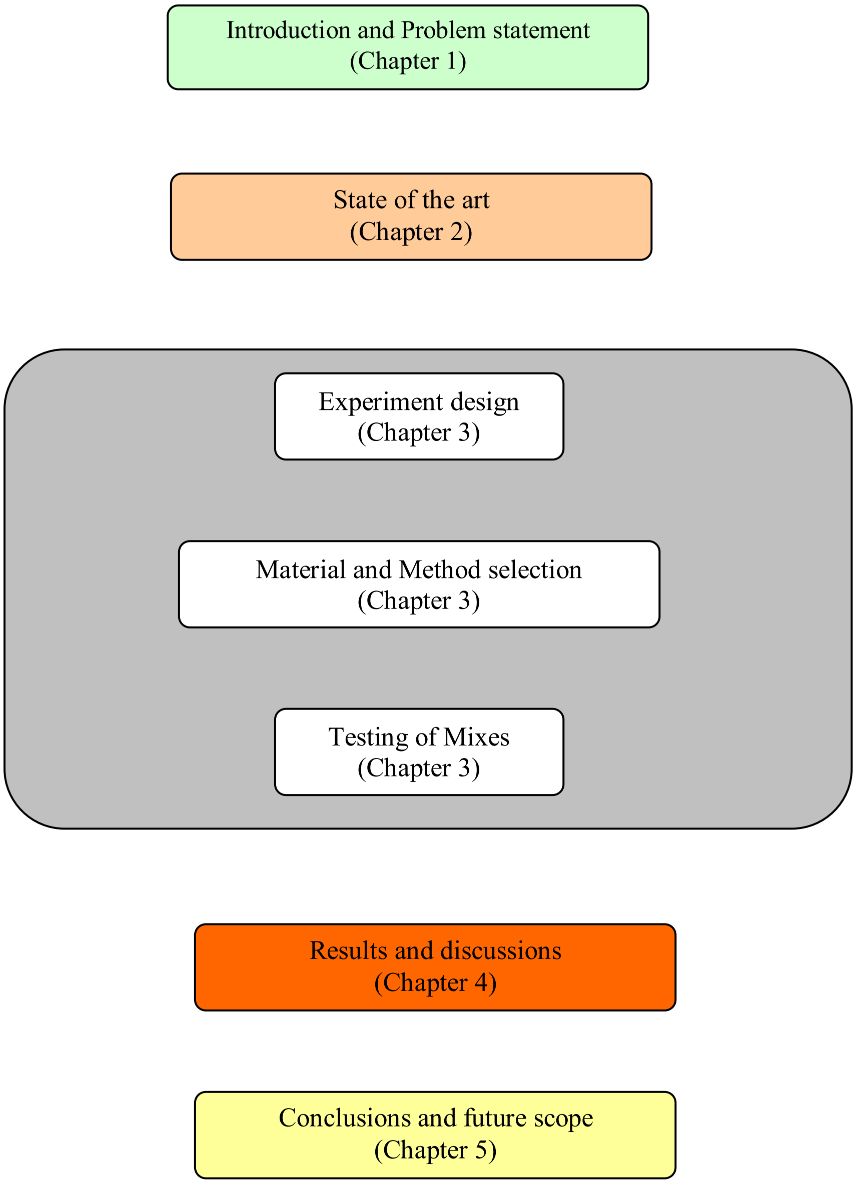

Figure 1 Thesis structure

Synopsis

RCC has been well established for the hydraulic engineering applications and gaining acceptance for pavement engineering applications. With its obvious technical and engineering advantages, it needs further exploration, as a material and as a *construction technique. Understanding of the mechanical properties is insufficient in describing the durability performance of concrete. With the inbuilt heterogeneity of the material and differences in the measurements of its durability related characteristics, there is thus a need for explaining the fundamental nature of water transport in Roller compacted concrete. This will pave the way to a better understanding of the material behavior in response to environmental-, hydro-, thermal-, and mechanical loading. In addition to this understanding of microstructure of the cement paste and the aggregate-paste inter-phase would assist characterizing the material for durability and would initiate further interest and research.*

2. STATE OF THE ART

Summary

This chapter provides a review of existing state-of-research on the subject matter of RCC. The chapter begins with the definitions of RCC and covers the possible range of applications. Initially the consistency, workability and compaction characteristics of the mixes are reviewed followed by an appraisal on the mechanical properties of RCC. Durability is addressed in the terms of permeability, sulphate attack, abrasion resistance, Freeze-Thaw resistance, etc. This chapter also covers a summary of the mix proportioning methods. A review of the physics of water transport in concrete via different mechanisms is presented to prepare the background for presented study.

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2.1 Introduction

RCC is a rapidly evolving concrete material and construction methodology. Due to its unique nature, it is applied widely in diverse engineering applications ranging from hydraulic to pavement structures. Deriving its origin from soils' approach of compaction, RCC has evolved significantly offering sound engineering benefits and cost effectiveness. Being distinctly different in its macro- and micro-structure, RCC offers itself as an anomalous material at times. Growing interest in a wide range of applications of RCC has lead to many laboratory and field studies and investigations. Moreover this is also motivating exploration of various characterizing and durability related studies. Most of these are restricted to one application or the other in a specific climatic region. There is however a need for unifying studies that characterizes some aspects of this unique material in a holistic manner.

This chapter is dedicated to an appraisal of relevant theoretical and experimental studies done till date. Initially the uniqueness of the material is discussed along with its applications and comparison with CVC. Subsequently, various fresh, mechanical and durability characteristics of RCC are discussed in brief. A section is then devoted to the understanding of the water transport phenomena in concrete, in general and to sorptivity in particular. Special section on the F-T resistance of RCC institutes the existing state of knowledge on the said property. Further to this, various mix design strategies are highlighted. Finally the chapter concludes with a synopsis of the research needs and identifies them with the current study.

2.2 RCC: A Unique Material

ACI 116 [1] defines RCC as

"Concrete compacted by roller compaction; concrete that, in its hardened state, will support a (vibratory) roller while being compacted."

While the ACI 325 committee [2] describes RCC as

"A relatively stiff mixture of aggregate [maximum size usually not larger than 19 mm (¾ in.)], cementitious materials and water that is compacted by vibratory rollers and hardened into concrete. When RCC is used as a surface course a minimum compressive strength of 27.6 MPa (4000psi) is generally specified.

What makes RCC unique is its nature in terms of its consistency! The consistency of RCC is very dry nearing that of soil during compaction. Furthermore the concept of w/c ratio in general is not valid for specifying RCC mixtures. Instead the concept of optimum moisture content (OMC) and maximum dry density (MDD) is more relevant and applicable. Unlike conventional concretes that are consolidated using internal or external vibrators, RCC is compacted using rollers. The resulting structure of concrete bears a very good aggregate skeleton that imparts a significant amount of strength to the concrete. Unlike CVC, this is turn leads to a considerably higher mechanical strength. At the same time due to very nature of consolidation, this concrete material contains relatively higher amount of compaction voids. Moreover, due to the unique nature of consistency, the paste in RCC is heterogeneous and variable.

As stated previously, RCC is applied in two general areas of engineered construction viz. hydraulic and pavement structures. It is recognized as probably being the most important development in concrete dam technology in the past quarter century; and a relatively recent and evolving technology for pavements. Usually mixed using high capacity continuous mixing and batching plants, RCC has a consistency of damp gravel or zero slump concrete. Delivered in dump trucks; on conveyor belts and at times in transit mixers, RCC is then spread using bulldozers (for dams) and/or asphalt or slip form paving machine (for pavement wearing course or base layers) and compacted in layers ranging from 100 mm (4 in.) to 300 mm (12 in.), depending on the application, availability of compaction equipment, space considerations and consistency. Generally the desired level of compaction is achieved using vibratory rollers. Occasionally the compaction may be provided using rubber tire rollers or large internal vibrators mounted on backhoes or bulldozers. The latter methods of compaction are not preferred from the quality control/quality assurance (QC/QA) perspective.

As a material, RCC handles initially like a soil and sets up later to be a true concrete or *concrete-like* material, thus making it a unique combination of *soil-concrete*. Engineers designing RCC projects therefore come from a diversified background ranging from structural, geotechnical, geological, general civil, transportation and hydraulic specialties [3]. Potent of accommodating a wider range of materials, this material and method offers engineering advantages in the form of reduced materials' cost, increased placement speed, and reduced time for construction and lower maintenance costs.

2.3 Range of Applications

History of RCC can be found in the literature [2, 4]. Table 1 exemplifies some of the significant applications of RCC in hydraulic and pavement structures. Figures 2 and 3 illustrate a couple of examples of applications of RCC.

Table 1 Applications of RCC

Structure	Application (*example*)	Structure	Application (*example*)
Pavements	• Pavement bases (*Highway construction in India*) • Low maintenance roads and parking areas (*General Motors, Spring Hill TN, USA*) • Industrial access roads surfaced with or without asphalt or concrete overlay (*Tennessee DOT*) • Inlay rehabilitation (*City of McMurray, AL, Canada*) • Fast track intersections (*Calgary, AL, Canada*) • Shoulder reconstruction (*Atlanta, GA, USA*) • City streets (*Lane Avenue, CO, Ohio, USA*)	Hydraulic	• Gravity dams (*Upper Stillway dam*) • New spillways (*Cold Springs dam, Oregon, USA*) • Downstream buttress (*Camp Dyer diversion dam, Arizona, USA*) • Overtopping protection for embankments (*Vesuvius dam, Ohio, USA*) • Upstream slope protection (*Jackson lake dam, Wyoming, USA*) • Erosion protection (*Ochoco dam, Oregon, USA*) • Hydraulic structure foundation and buttress (*Pueblo dam spillway, Colorado, USA*)

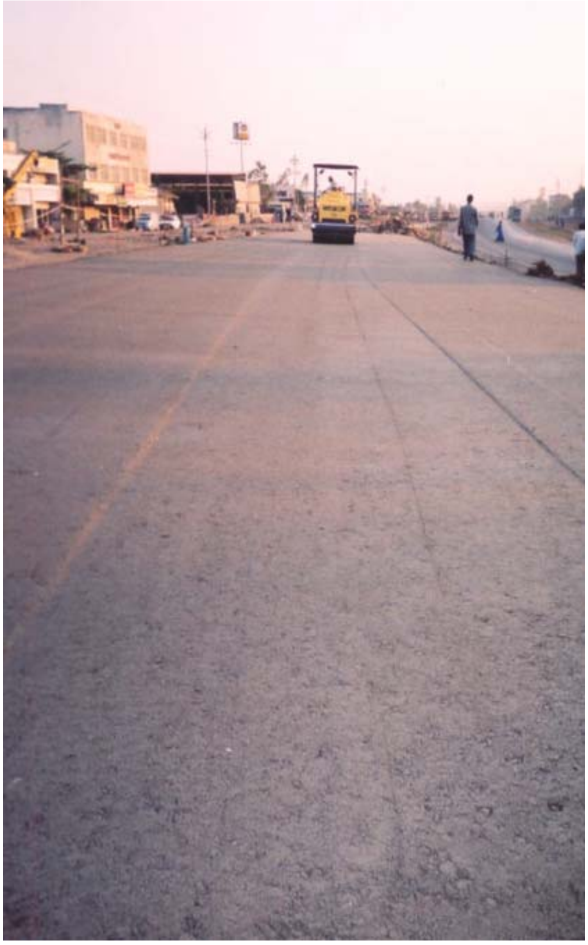

Figure 2 Roller compacted concrete used as rigid pavement base in India

Figure 3 RCC used as Pavement shoulder in Atlanta, GA, USA [5]

2.4 RCC versus Conventional Concrete: A Comparison

Table 2 compares and contrasts the properties of RCC with conventional concrete.

Table 2 RCC vs. Conventional concrete

SN	Point	Conventional concrete	Roller compacted concrete
1.	Consistency	Can be measured by slump test, flow test, etc. Vebe test is not helpful in predicting the consistency of concrete	Measured by Vebe consistometer. Value depends on the type of consistometer used and application of RCC
2.	Cement content	Decided by the water demand of the aggregate system and w/c ratio of the mix	Decided on % by weight basis and is relatively lesser for comparable compressive strength
3	Moisture content	Given by w/c ratio by weight	Given by optimum moisture content
4	Theoretical air-free density (NMSA 19 mm)	Usually close to or greater than 98 % depending on mix constitution	Usually close to or less than 98 % depending on the mix proportioning method
5	Aggregate grading	Comparatively less well graded	Very well graded to minimize voids
6	Fresh concrete specified in terms of	Slump and temperature	Vebe consistency, optimum moisture content and maximum fresh (dry) density
7	Concrete mixing	Mostly mixers	Mixers or pug mills depending on the application
8	Transportation	Usually through transit mixers	By scraper, conveyor, bottom and rear dump trucks or large front end loaders
9	Spreading and laying	By pumps, slip form paving machines, and/or manually	By back hoe, loader, asphalt paving machine, etc. Mostly methods used for soils are used.
10	Compaction	Usually using internal or external vibrators	Roller
11	Strength	Relatively lesser for the same cement factor	Relatively more for the same cement factor
12	Permeability	Relatively lesser	Relatively higher
13	Surface finish	Smooth	Rough and wavy due to roller compaction
14	Air entrainment for Freeze-Thaw resistance	Required with specific spacing and distribution	May or may not be required

2.5 Fresh Properties of RCC

This section discusses important fresh properties of RCC. The influencing factors for these properties are also briefly discussed.

2.5.1 Consistency

Consistency is primarily a measure of wetness of concrete. The main factor affecting the consistency of concrete in fresh state is the free water content, because by simply adding water to the mixture, inter-particle distance and lubrication among the solid particles are increased. Free water content has been verified to have a relationship with the consistency of fresh concrete [7].

Unlike conventional concrete, RCC mixtures are very stiff. To measure this stiff consistency, Vebe consistometer is used. This test is good laboratory test particularly for very dry mixes. Additionally, it simulates the field placement method of concrete [6]. However, there are minor differences in the methods of measuring the Vebe consistency of concrete depending on the dryness of concrete, its application and the National code or test standard being followed. Table 3 provides a summary of this comparison. It has been reported that the heavier the surcharge, the smaller the Vebe time (VBT) of vibration required [8]. One of the interesting features of this test, like the slump test is that it is highly subjective and more often than not this feature limits its application in practice.

Table 3 Surcharge weights in Vebe tests [8, 9]

SN	Code of Practice	Surcharge used for the test (kg)	Remarks
1	Japan	20.0	8
2	US Bureau of Reclamation	22.7	8
3	US Corps of Engineers	12.5	8
4	India	0.0	9

In a study [10] for developing the vibration consistency prediction model for RCC, researchers developed correlations between the Vebe time and free water content of the mixes. These plots are shown in Figure 4.

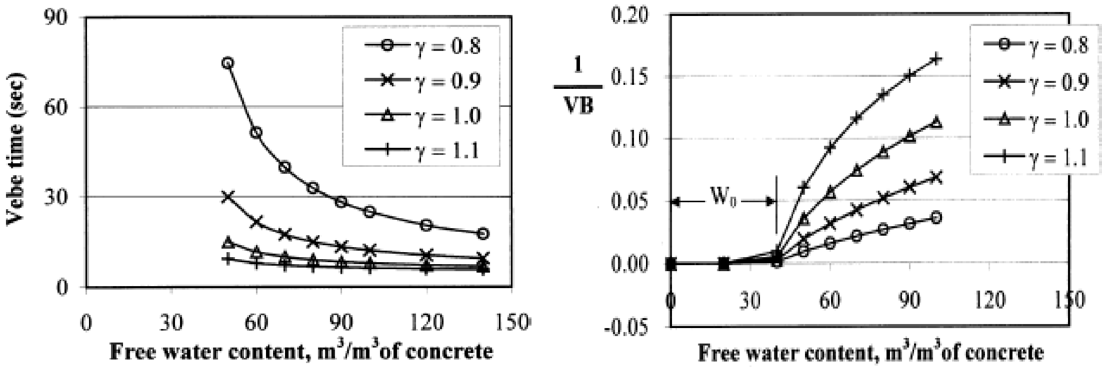

Figure 4 Relationship between Vebe time and free water content [10]

Here,

$$\gamma = \frac{V_{paste}}{V_{void}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

The following remarks were presented for these curves:

1. If the free water content of the mix is less than a particular value, the Vebe time increases dramatically. This is because the amount of free water is not sufficient to overcome the inter-particle surface forces among the solid particles, which include friction and cohesion among the solid particles.
2. The Vebe time decreases with increase in γ. This happens because in concrete with larger paste content, aggregates are well dispersed and have a larger inter-particular distance in the paste. This results in better deformability of the mixture and less time for the paste to rise up and fill all cavities under the surface of glass plate rider used in the VBT.

The researchers also proposed models and validated these by actual testing. The significant conclusions are summarized as follows:

1. Free water was verified to have a relationship with deformability and Vebe time of RCC. Free water can be obtained when unit water content, water retainability of powdered materials and surface water retainability of aggregates, and the additional free water content from fillable powder are known. Equations for reaching these values were presented in the publication.
2. The amount of minimum free water required for making RCC workable is considered to be directly affected by inter-particle surface forces among solid particles in the mixture and can be formulated with the effective surface area of the solid particles in the mixture and concrete temperature.

2.5.2 Workability

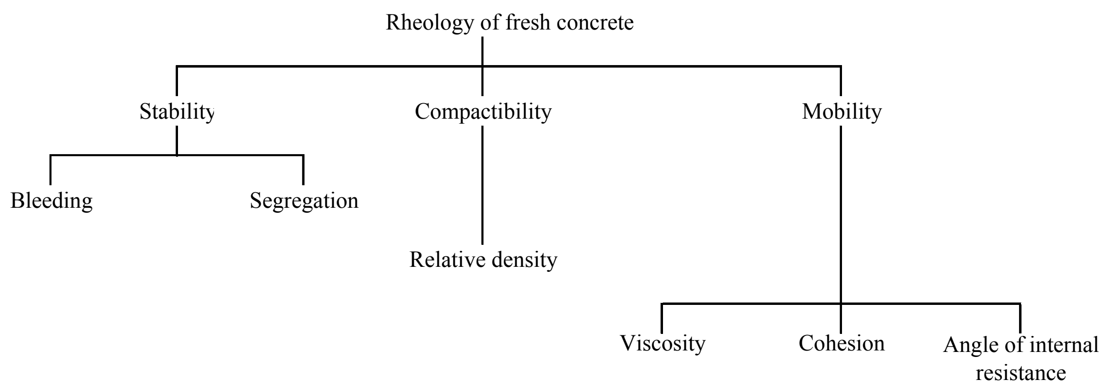

Figure 5 Factors influencing the rheology of concrete [12]

The cost of placing concrete is critically dependent on its workability, and uniformly good characteristics in the hardened structure are possible only with adequate flow without segregation. The importance of workability of concrete has been universally recognized and is well-known to be affected by the variables including w/c, aggregate gradation, admixture type and dosage, among others [11]. Rheology of the concrete plays a crucial role in deciding the workability of concrete. Figure 5 shows the factors influencing the rheology of fresh concrete [12].

Initial studies have well established the appropriateness of RCC to the required riding quality for wearing courses for roads [13]. Bleeding is not a problem in RCC due to its dry nature. Segregation on the other hand is an issue since, RCC mixtures, due to their granular nature tend to segregate. This is controlled by proper aggregate grading, moisture content and adjusting fines content in lower cementitious content mixes. Higher cementitious mixtures are usually more cohesive and less likely to segregate [4].

Extremely dry concretes, compacted to high densities using powerful vibratory efforts, sometimes retain porosity of several percent in the hardened concrete because of an inappropriate mixture and/or insufficient compaction. Low density concrete is not able to attain high strength and long term durability [14-17]. Compactibility of RCC is considered to be an important factor to prevent void formation in the hardened concrete. Test methods on compactibility of RCC mixtures have been developed in the form of compactibility indices in the form of initial-filled volumes ratio, ultimate filled volume ratio, consolidating efficiency and energy. These indices can be used for predicting the appropriateness of RCC mixtures for pavements [18-20].

2.5.3 Moisture-density Relationships

Developing moisture-density curves is crucial in soils approach of RCC mix proportioning. The values of OMC-MDD are then used in actual laying and compaction of concrete with suitable moisture adjustments for evaporation losses during the transportation and laying of concrete.

Conventional specimen casting procedure standardized for CVC cannot be used for RCC due to its stiff consistency. Moreover the sample making procedure should be representative of the field method of compaction. Although a number of procedures are available for compacting representative samples, none have yet been standardized. The procedures frequently used involve vibrating the fresh RCC sample on a vibrating table under a surcharge, or compacting the sample with some type of compaction following the procedures of ASTM D 1557 [2] or using a vibrating hammer following ASTM C 1435 [21] or a gyratory compactor [22].

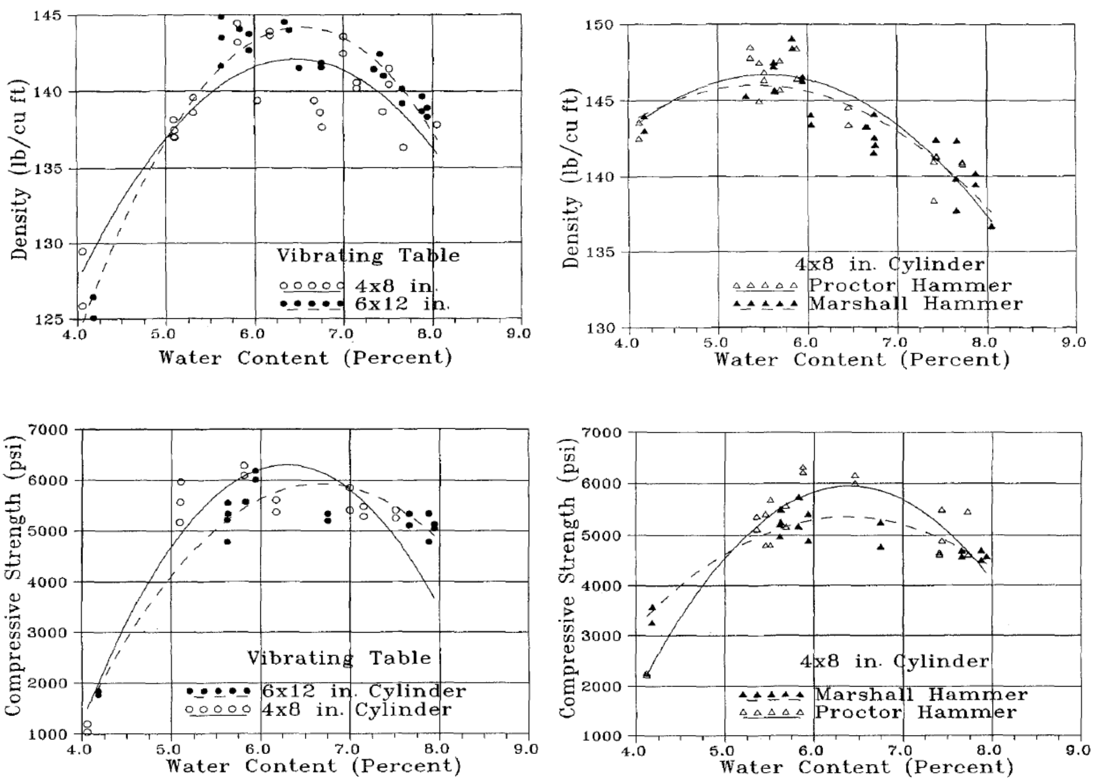

Figure 6 Effects of change in compaction energy [23]

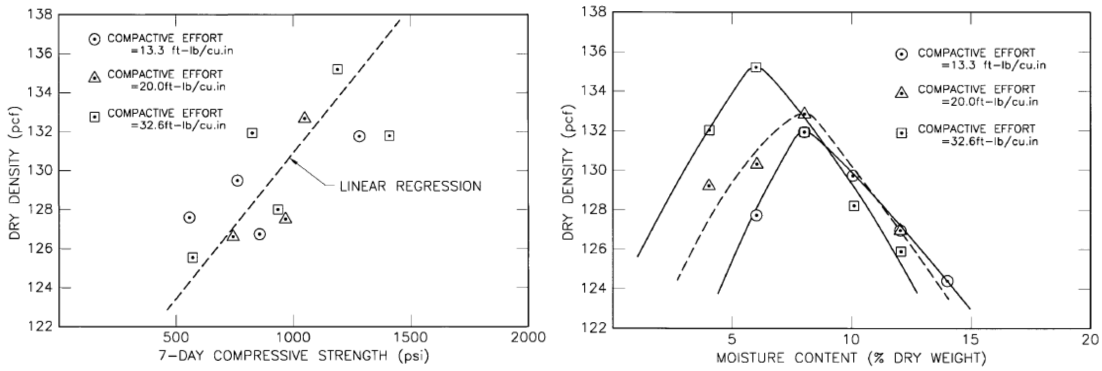

Figure 7 Effects of change in compaction energy [24]

Limited comparative studies are conducted on various methods of specimen formulation. [23, 24] Figures 6 and 7 show some of the results of these investigations. In addition to this, the specification of relative maximum fresh density and hence the dry density for practical purposes needs to be calibrated for specifying a target density. Higher the MDD achieved in laboratory trials, lower will be the relative density when compared with the practical density obtained in the field. Another important issue with this is the relative amount of confinement from the mold walls. This can change the densities by a significant amount depending on the concrete consistency and size of the specimen.

2.6 Mechanical Properties

Although RCC has been used for paving for more than a few years, only a limited number of investigations have been carried out to evaluate its engineering properties. Currently, no internationally standardized procedure exists for fabricating and testing RCC specimens in the laboratory. Thus it is not possible to directly compare properties of laboratory prepared RCC specimens without considering the procedures to fabricate the specimens. Consequently, the database on engineering properties of RCC is based primarily on tests of specimens (cores and beams) obtained from actual paving projects or from a few full-scale test sections [2] and a few laboratory studies [25-29].

2.6.1 Compressive Strength

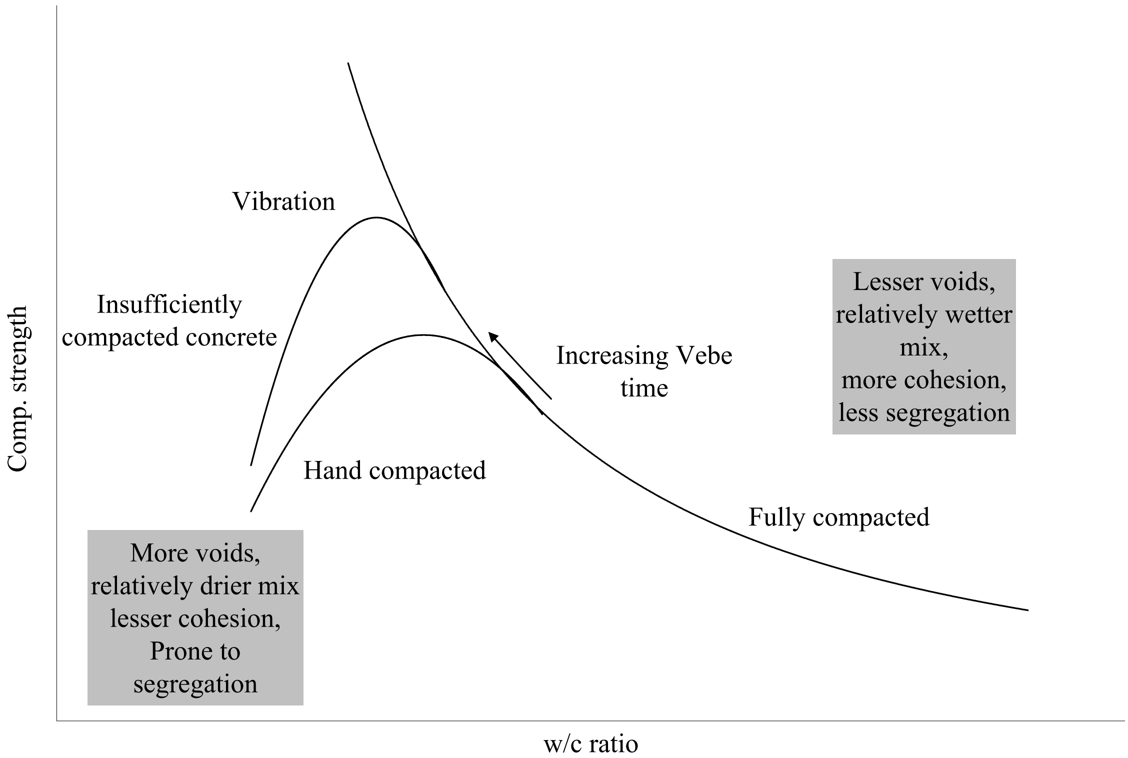

Figure 8 General relationship between compressive strength and w/c

The compressive strength of RCC increases with reduction in w/c ratio as long as *full compaction* is achieved. In addition to this, the compressive strength is determined by the water content, cementitious content, and properties of cementitious materials, the aggregate grading and nature of compaction. Water content less than the optimum moisture content would lower the strength. Moreover, lower cementitious content mixtures may not achieve the required strength levels if the aggregate voids are not completely filled. These facts indicate that the presence of voids in the mixture has a greater negative effect on the strength than the positive effect of water reduction [30]. These facts are graphically represented in Figure 8.

With regard to the temporal evolution of the compressive strength of RCC, mixes could be classified according the binder used in the mixture. In general, by increasing the binder content the strength also increases. A normal way of correlating compressive strength and cementitious materials is by using Mix efficiency or η factor given as

$$\eta = \frac{Compressive\_strength(kgf/cm^2)}{Cementitious\_material(kg/m^3)} \quad \text{………………….. … (2)}$$

Exemplary mix strengths could be obtained from the above references.

2.6.2 Flexural Strength [2]

Flexural strength (f_r) measured by third point loading can be estimated using the compressive strength (f_c) following relationship:

$$f_r = C\sqrt{f_c} \quad \text{………………………….. (Eqn. 2-3)}$$

Where

C is a constant between 9 and 11, depending on actual RCC mixture.

Exemplary data is available in the reference.

2.6.3 Splitting Tensile Strength [2]

Splitting tensile strength of cores obtained from actual RCC pavement projects range from 2.8 to over 4.1 MPa. Splitting tensile strength of RCC cores are more easily and reliably measured than the flexural strength tests on sawed beams. Exemplary data is available in the reference.

2.6.4 Modulus of Elasticity [2, 4]

Modulus of elasticity has generally not been measured on specimens from actual RCC projects. Limited tests on cores indicate that the moduli of elasticity for RCC may be similar or slightly higher than those of conventional concrete with similar cement content. Exemplary data is available in the references.

2.7 Durability

Inadequate durability manifests itself by deterioration, which can be due either to external factors or to the internal causes within the concrete itself. The various actions could be broadly divided into physical, chemical or mechanical. The damaging action can be of various kinds and can be direct or indirect and the deteriorating mechanism of concrete is rarely due to one isolated cause. Figure 9 illustrates a broad classification of the deteriorating mechanisms in concrete. It is important to note that the physical and chemical processes of deterioration act in a synergistic manner. Brief reviews of all the deterioration mechanisms of concrete are available in [6, 31].

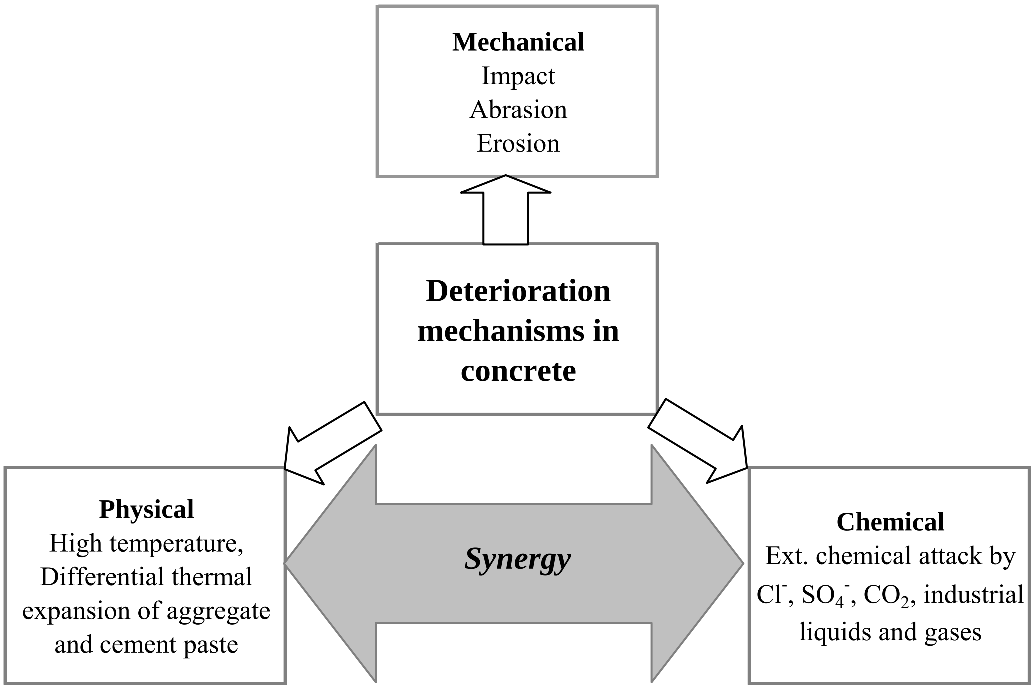

Figure 9 Mechanisms of concrete deterioration

It is difficult to assign deterioration to a particular factor, but the quality of concrete, in the broad sense of the word, though with a special reference to permeability, nearly always enters the picture. Indeed, with the exception of mechanical damage, all the adverse effects on the durability involve the transport of fluids through concrete. Hence the fluid transport in concrete is the most important phenomenon from the durability perspective [6].

2.7.1 Microstructure of Concrete: Media for Flow

At the microstructural level, there are two components of the structure viz. hydrating cement paste and the transition zone, which are subjected to changes with time and environmental conditions. This makes concrete a living system and also decides the physical properties of concrete like absorption and permeability. The structure of hydrated cement paste consists of the following three types of pores in hardened cement (Refer Table 4) paste from the context of permeation characteristics of concrete [32]. While Figure 10 shows the composition of hydrating cement.

Table 4 Types of pores in concrete

SN	Type of pore	Size range (A)	Role in water transport
1	Interlayer space in calcium silicate hydrate	5-25	Do not contribute to water transport
2	Capillary pores	100-500 (well hydrated, low w/c) 3000-5000 (early age, high w/c)	Capillary suction
3	Air voids		
	a. Entrapped	$\approx \leq 3 \times 10^7$	Significant role in permeability of concrete
	b. Entrained	$0.5\text{-}2 \times 10^6$	

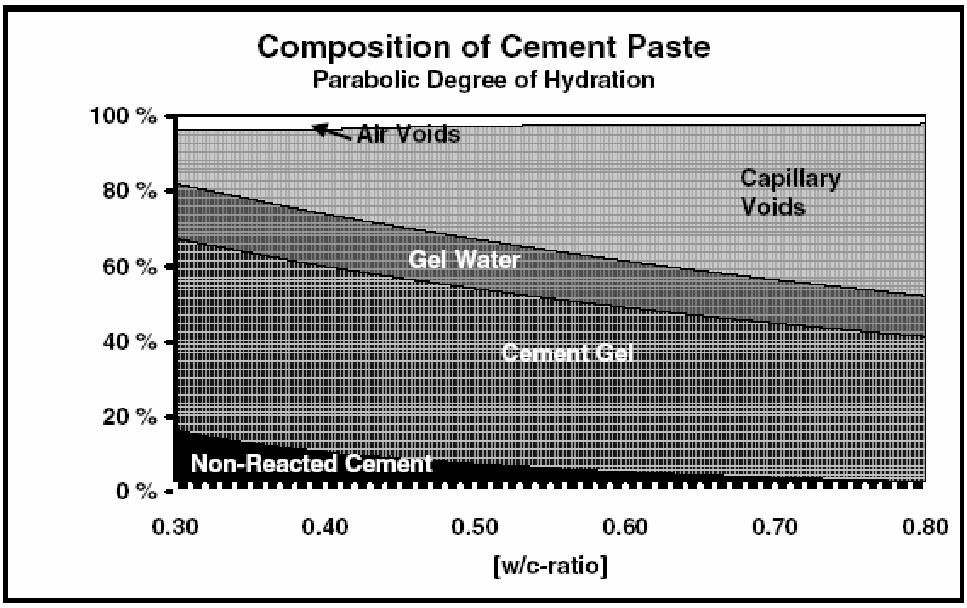

Figure 10 Composition of concrete [33]

2.7.2 Water Transport in Concrete

Table 5 Water transport in concrete

SN	Effect/ Process	Definition	Mathematical treatment	Remarks
1	Diffusion/ Diffusivity	Transfer of mass by random motion of free molecules or ions in the pore solution from regions of high concentrations to regions of lower concentrations of the diffusing substance	$F = -D(dc/dx)$	35
2	Sorption/ Sorptivity	Transport of liquids in porous solids due to surface tension acting in capillaries	$a = \Delta m/Af(t^n)$	36
3	Permeation/ Permeability	Flow under applied pressure difference or gravity	$k_w = (Ql)/ (tA\Delta h)$	37
4	Migration	Transport of ions in electrolytes due to the action of electrical field as driving force.	$J = D(dc/dx) + (ZF)(DC)/RT(dE/dx) + CV_e$	38
5	Adsorption	Fixation of molecules on solid surfaces due to mass forces in mono- or multimolecular layers	DNA	39
6	Desorption	Liberation of adsorbed molecules from solid surfaces	DNA	40

Note: Remarks column represents the reference numbers from which data was extracted

During their service life, many of the cement based structures are exposed to various types of aggression where, in most cases, the deterioration mechanisms involve transport of fluids and/or dissolved chemical species within the porosity of the material. This transport of matter (in saturated or unsaturated media) can be due, either to pressure gradient (permeation), a concentration gradient (diffusion), capillary suction (sorption) or release (desorption) or to the application of electrical field (migration) [34]. Table 5 provides a summary of the important transportation processes involved in water transport of concrete along with their mathematical treatment. These processes are not discussed in detail except for sorptivity, which forms a major part of this research.

With sustainability concerns becoming grave, constructing durable and long lasting structures is becoming greater than ever critical. One of the main culprits associated with the bulk-deterioration of concrete is the ingress of water through the surface skin. The situation is further exacerbated by the presence of deleterious ionic species dissolved in the invading water [40]. Consequentially, there is an increasing concern that the water movement/transport contributes to most of the deterioration processes of the bulk properties of concrete such as chloride- and carbonation induced corrosion, leaching, acid and Sulphate attacks, Freeze-Thaw attacks as well as alkali-silica reaction, and therefore may have decisive effects on its performance [41-44]. The transport of aggressive gases and/or liquids into concrete depends on its permeation characteristics. As the permeation of concrete decreases, its durability performance, in terms of physiochemical degradation increases. Therefore, permeation of concrete is one of the most critical parameters in the determination of concrete durability in aggressive environments [45].

Table 6 Influencing factors for water transport in concrete

SN	Effect/ Process	Driving force(s)	Factors affecting: Time (s)	Concentration (g/m^3)	Viscosity (Ns/m^2)	Density (kg/m^3)	Surface tension (N/m)	Temperature (K)	Physiochemical. Nature -	Remarks
1	Diffusion/ Diffusivity	Concen. gradients	×	×	DNA	DNA	×	×	×	35
2	Sorption/ Sorptivity	Capillary suction	×	NA	×	×	×	DNA	×	35
3	Permeation/ Permeability	Pressure difference	×	NA	×	×	DNA	×	×	36
4	Migration	Diffusion + migration +convection	×	×	×	×	×	×	×	37
5	Adsorption	Concen. and temperature gradients	×	×	DNA	DNA	DNA	×	×	38
6	Desorption		×	×	DNA	DNA	DNA	×	×	39

Notes: NA – Not applicable; DNA – Data not available;

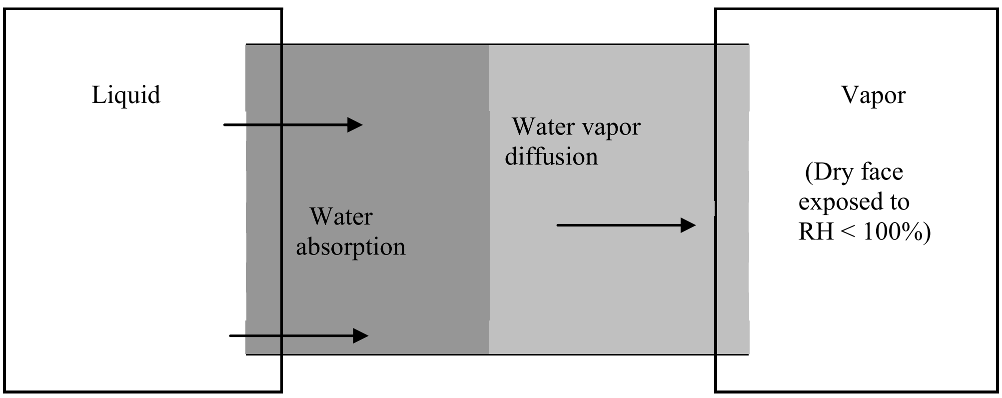

Figure 11 Wick action in concrete (Proceeding water front)

Another related process worth mentioning is wick action, which is defined as the transport of water (and any species it may contain) through the concrete element from a face in contact with water to a drying face (Refer Figure 11) [51]. This term is often applied to a steady process in which the capillary flow rate of the liquid is equal to the evaporation rate [52, 53]. Wick action has been considered a combination of capillary absorption and water vapor diffusion with evaporation as being the linking process.

2.7.3 Permeability

Concrete permeability depends on a vast range of parameters, which can be grouped together into several categories as:

1. Constituents characteristics
2 Sample characteristics
3 Stress conditions

Figure 12 shows the interplay of the factors influencing concrete permeability. In a nutshell, the permeability of mass of concrete is almost totally controlled by the mixture proportioning, quality control and degree of compaction.

A detailed review of the subject matter is beyond the scope of this work. Important parameters related to this work that might have an influence on the performance characteristics of concrete are

1. w/c ratio
2. Degree of hydration
3. Aggregate porosity
4. Degree of consolidation
5. Cracking

When there are sufficient fines, controlled fine particle size distribution to minimize the air void system and full compaction, RCC will be relatively impervious. In general, an unjointed mass of RCC made from clean conventional aggregates with sufficient paste or very lean mixtures with controlled aggregate grading containing sufficient fines will have permeability values similar to conventional concrete (CVC). Joints between the layers may be a cause of concern. RCC permeability coefficient ranges from 10^{-6} m/s to 10^{-12} m/s with cementitious content from 60 kg/m^3 to 250 kg/m^3 as compared to 10^{-9} to 10^{-12} for CVC with similar cementitious content [54].

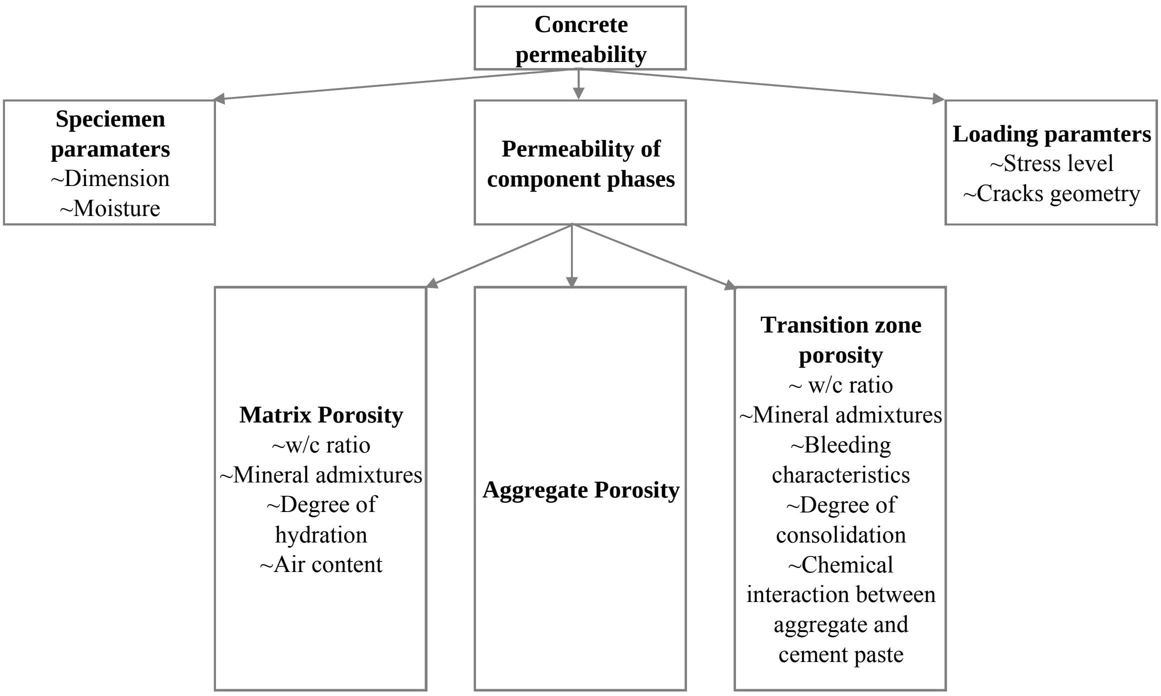

Figure 12 Components of concrete permeability

In a study conducted on cores extracted from the paved RCC, the researchers observed and offered comments as follows:

1. RCC was found to be considerably more permeable than the conventionally proportioned and placed concrete, and somewhat more permeable than conventional concrete.
2. There was no difference observed in the permeability of the top and bottom part of the cores from pavement, indicating that more or less uniform compaction could be achieved throughout the depth (150 to 170 mm).
3. Having a higher w/c ratio in RCC is both advantageous and disadvantageous from the permeability point of view. There could be a w/c ration expressed as OMC that could possibly provide the least permeable concrete.
4. The use of finer cement appears to be reducing the coefficient of permeability.
5. The microstructure of concrete showed a porous structure and presence of deformed air bubbles due to compaction process.
6. Permeation in RCC takes place either through the interconnected compaction voids or through poorly formed porous aggregate-paste interfaces. These less-than intact interfaces also account for the poor moduli of elasticity, tensile strengths and fatigue limits of such concretes.
7. It was hypothesized that having a high permeability coefficient was in fact helpful in improving the internal cracking resistance under Freeze-Thaw cycling, by allowing lesser movement of water through the body of concrete.

2.7.4 Sulphate Resistance

Sulphate attack is not widespread in occurrence except in some areas and the amount of extensively gathered laboratory knowledge is inadequately substantiated by field research. Sulphate attack involves all the chemical changes involving sulphate ion that produce damaging physical consequences. In his classic review [55] on the subject matter of sulphate attack, Neville deals with various mechanisms, chemical reactions involved in sulphate attack and specifications related to concrete susceptible to sulphate attack. In this review, the author emphasizes the significance of using low w/c, dense, well compacted and well cured concrete for harnessing sufficient sulphate resistance. In addition to this, the author states that the usage of ASTM Type V cement as against a low w/c ratio concrete is yet unresolved.

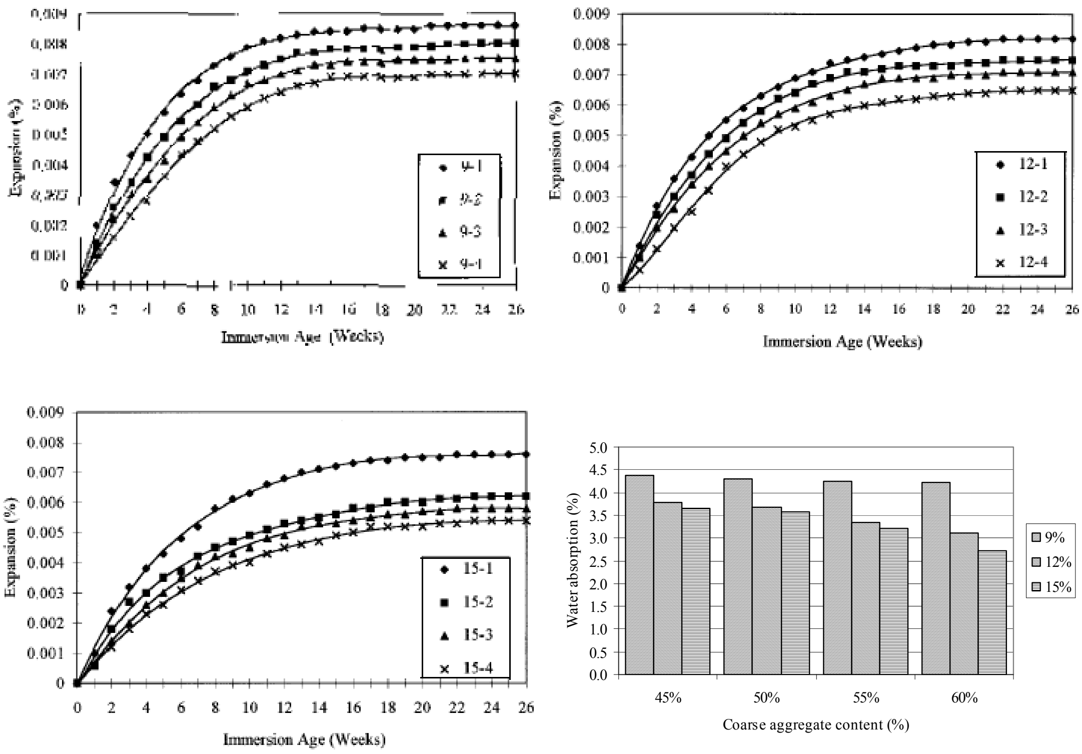

Figure 13 Effects of cement content and aggregate content on sulphate resistance [56, 57]

In few studies [56,57] conducted using ASTM Type V cement and class C fly ash as fine aggregate replacement and different coarse aggregate contents, it was found that

1. RCC with or without fly ash, exhibited good resistance to external sulphate attack. During the test period of six months, the sample showed continued but marginal expansion.
2. An increase in the cement content, to a greater extent, or coarse aggregate content, to a lesser extent, resulted in RCC specimens with lower absorption, higher strength and improved resistance to sulphate expansion and reduction in strength. Refer to Figure 13 for the an illustrative data showing the trends in expansion for three different levels of cement contents (9%, 12% and 15%) and four different % of coarse aggregates (viz. 1:45%, 2:50%, 3:55% and 4:60%).
3. There was continued expansion and the absence of mass loss or noticeable reduction in strength for RCC suggested a stronger presence of ettringite reaction over that of gypsum formation. This was attributed to the fact that RCC mixes contain lower amount of cement and limited amount of C_3A present in Type V cement

2.7.5 Abrasion Resistance

Limited number of studies are reported in the literature on this property of roller compacted concrete. Abrasion resistance is not a bulk property but a surface property that depends primarily on the surface layer characteristics of concrete [58] which in turn is recognized to be affected by the cement content, w/c ratio, slump, air content, type of finish and curing regimen [59].

In a study [60] comparing the abrasion resistances of field extracted and laboratory caste specimens, of identical composition, density and strength, the researcher found that

1. The abrasion resistance of the saw/cut sides is controlled by the exposed coarse aggregates, while the resistance of the top surface is controlled by the cementitious paste and fine aggregate.
2. In field, due to the consolidation provided by the tamping and vibration effects produced by the heavy-duty pavers and roller, the fine particles migrate to the top layer, making the top surface the densest and most binder-rich.
3. The abrasion resistance of the top-surface of field cut samples was far superior to the saw/cut side when tested under air-dry conditions and this difference reduced substantially when the testing was done under wet conditions.
4. The quality of the surface in contact with the mold is substantially lower than the corresponding field-cut samples.
5. Improper moist curing conditions impact the wearing surface more than the compressive strength.
6. It was recommended that periodic abrasion testing after laying and compacting the RCC pavement could be used for monitoring the surface performance as a function of curing time. Some of these results are shown in Figure 14.

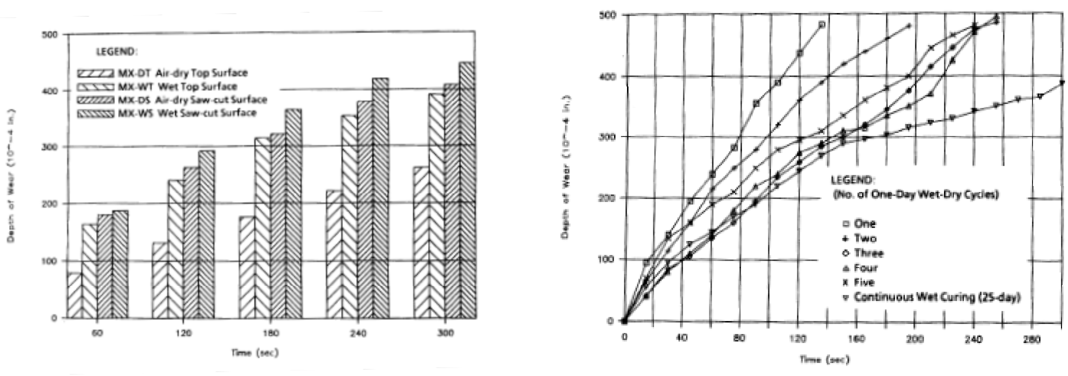

Figure 14 Effects of sample preparation on abrasion resistance [60]

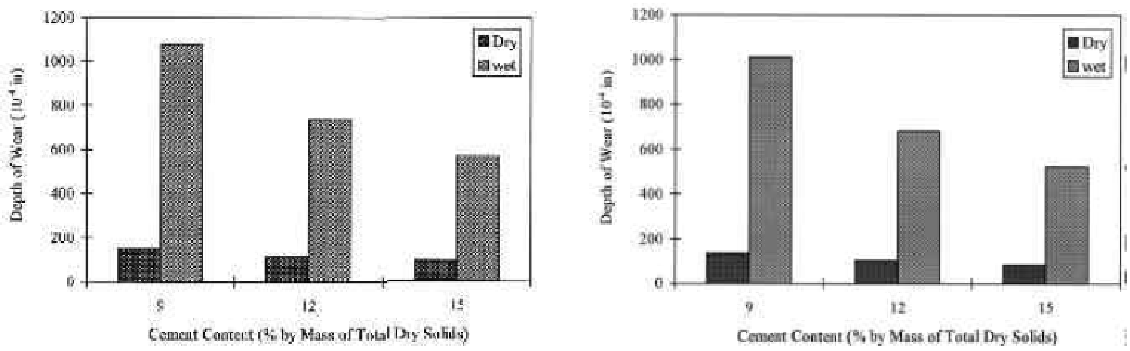

Figure 15 Effects of cement content on abrasion resistance [57]

In another study [57] (Refer to Figure 15) on laboratory made roller compacted concretes made with ASTM Type V cement (Crushed limestone with 25 mm NMSA) and incorporating dry bottom ash as fine aggregates, researchers found that

1. Increasing the cement content from 9 to12 to 15 % lead to decrease in the abrasion resistance by 32 % and 55 % respectively over 9% mixture. This was a consequence of the increase in the higher cement content enhancing consistency and compactibility of the matrix along with producing a stronger and smoother surface layer.
2. Similarly, but to a much lesser extent, increases in the coarse aggregate contents from 50 to 55 to 60% by mass of total dry solids (with equivalent decrease in the fine aggregate content and w/c ratio, resulting into relatively richer and denser paste) lead to a decrease in the depth of wear by 3.6 and 3.8% respectively.
3. The rate of abrasion decreased considerably with the testing time and cement content.
4. Irrespective of the mixture proportions, the abrasion resistance being a surface property in greatly influenced byte hg cementitious paste and sine aggregate of the top mortar, which is highly susceptible to moisture content. In these series of

investigations, the researchers found that irrespective of the composition of the RCC mixtures, the abrasion resistance was significantly higher under air-dry surfaces than that obtained under soaked testing conditions.

2.7.6 Drying Shrinkage

Table 7 Test matrixes for drying shrinkage study [61]

Grading	Moisture content		
	Dry of OMC (D)	OMC (O)	Wet of OMC (W)
Fine (F)	FD	FO	FW
Medium (M)	MD	MD	MW
Coarse (C)	CD	CD	CW

Drying shrinkage is influenced by several factors including the paste constitution, elastic moduli/compressibility of the aggregates, aggregate content, specimen geometry, age of concrete and the relative humidity around the concrete. A detailed discussion on this subject matter is available in [6, 31]. In a study (test matrix as shown in Table 7) [61]conducted on RCC mixtures incorporating 25 % fly ash to partially replace cement and partially provide fines passing 75 micron aggregates and with three different coarse aggregate (crushed limestone) grading viz. fine, medium and coarse graded (paste volume shown in the Figure 16), the researchers found that

1. The drying shrinkage values exhibited by different RCC mixtures for pavement applications (avg. 15 x 10^{-5}) are relatively low compared to the conventional concrete used for pavements.

2. The individual effects of moisture content and aggregate grading (paste volume) on the drying shrinkage of RCC mixes were not found to be significant, but their combined effects were significant.
3. As can be seen from the graph shown in Figure 16, it was observed that mixture CW produced the maximum shrinkage, while the mixture MO produced the least shrinkage.

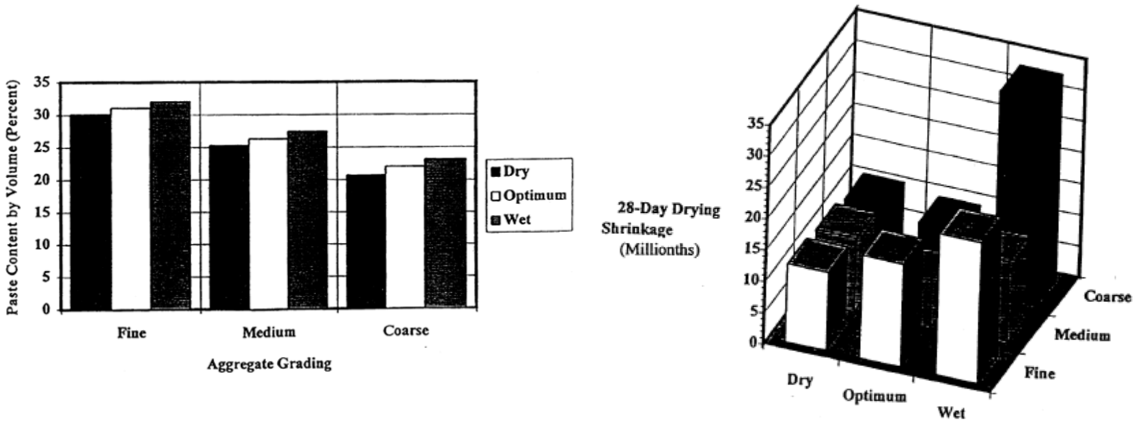

Figure 16 Effects of paste content and aggregate content on drying shrinkage [61]

In another study [62] (mix proportions similar to 57), the following observations were made:

1. At constant cement content, the drying shrinkage decreased as the coarse aggregate content increased, due the higher restraint offered by the higher aggregate content.
2. With increasing cement and hence paste content, the availability of the paste for shrinkage increases and is reflected in terms of increasing values of drying shrinkage. Some of the results of these investigations are shown in Table 8.

Table 8 Effects of cement and aggregate content on drying shrinkage [Values X×10^{-6}]

Cement content (%)	Aggregate content by weight (%)		
	50	55	60
9	248	218	203
12	270	236	217
15	298	277	255

2.8 Mix Proportioning Philosophy

The roller compacted dam (RCD) and roller compacted pavement (RCP) requires a laboratory trial and a field trial placement for correlating and confirm the mix design and rolling specifications. These correlations depend on a wide range of factors including the mix design, hauling and placing time, paver type and nature of compaction given by the paver, roller type and rolling scheme and environmental conditions. At times visual observations are made for deciding the mix proportion to be adopted and this to a large extent depends on the evaluator's subjective observations.

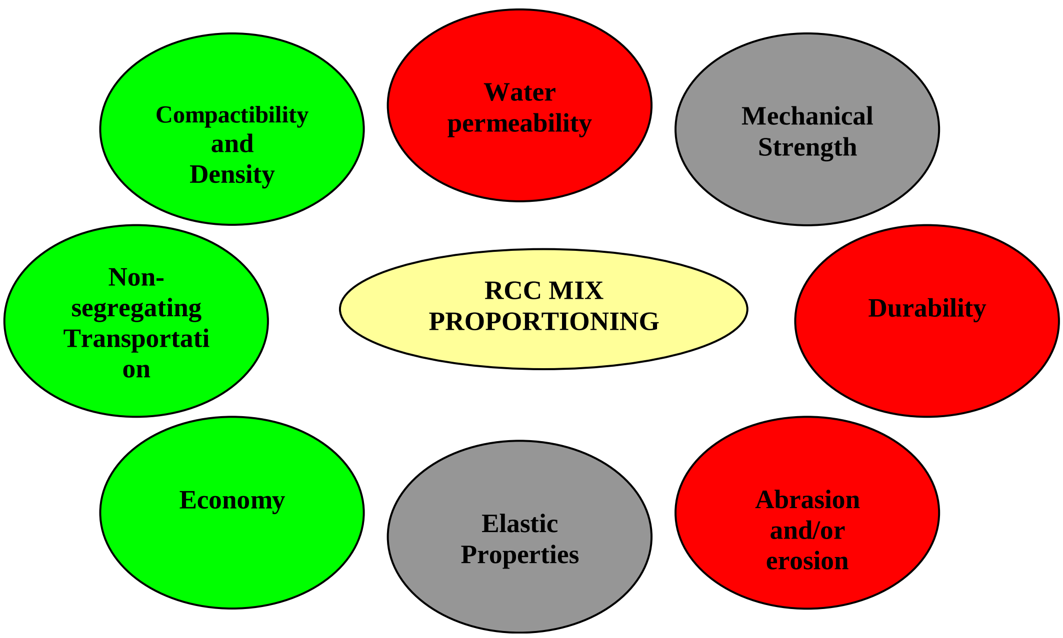

Figure 17 RCC mix proportioning: Influencing factors

Like conventional concrete, the primary objective of proportioning RCC mixes is to achieve an adequate and economic combination of binder, aggregate, water and admixtures which conform to the required specifications throughout its service life. There are many ways of reaching the objective. One of the important aspects of proportioning RCC mixes is that compressive strength unlike conventional concrete does not govern the mix proportioning. Depending on the application, shear, bending tensile or splitting tensile strength may dictate the proportioning. For example shear strength of RCC governs its proportioning, if it is used for hydraulic structures like dams; while flexural or bending tensile strength governs its proportioning, if it is used for pavement structures. In addition to this RCC exposed and submitted to severe climatic conditions and high seismic accelerations must be proportioned for durability. Figure 17 shows the factors influencing the RCC mix proportioning.

The primary considerations while proportioning RCC mixes is to gain a substantially lower consistency, often measured by Vebe consistometer; a non-excessively subsiding mix capable of supporting the load of a vibrating roller and finally an appropriate grading and paste volume to consolidate adequately under the available rolling scheme.

2.9 Sorptivity

When a homogeneous porous material has a constant hydraulic potential at wet front, liquid can mount to considerable heights due to capillary absorption. In concrete this absorption of water by capillary pores and transport by capillary action into unsaturated or partial saturated concrete is defined as sorptivity. Since it mimics the processes that reduce the concrete durability, particularly the ingress of water, which may contain injurious dissolved salts, therefore it is a very appropriate index of durability [63]. It is the most important measurable property of porous material [64]. Physically, sorptivity quantifies the tendency of a material to absorb and transmit water and other liquids by capillarity [65]. (Note: hereafter in this thesis, sorptivity will exclusively mean water sorptivity, unless otherwise stated) Although not sufficient to substitute for complete characterization of the hydraulic properties of concrete, it serves as a valuable guide to capillary behavior. In addition to this, it gives the maximum rate of absorption of water by porous material; provides an estimate of the distance of penetration at any time, t of the notional sharp front; shape of the water content profile during absorption.

2.9.1 Physics of Water Movement and Analytical Treatment

When two dissimilar materials, such as two immiscible fluids or a fluid and a solid, are brought into contact with each other, surface tension forces arise due to the energy needed to form an interface. These surface tension forces can also create pressure drops and could lead to fluids flow in either direction depending on the nature of the materials and resulting forces. A brief derivation of capillary rise equation has been provided in the appendix.

The theory of unsaturated macroscopic flow of water in mortar and concrete bears its roots in the development of the theory of macroscopic flow in unsaturated porous media, initially introduced in soil physics [65-68]. This was based on Buckingham law of capillary flow (sometimes called as extended Darcy equation) [69]:

$$u = -K\nabla\Psi \quad \text{(Eqn. 2-4)}$$

Where,

u is the local vector flow velocity and is controlled by local capillary pressure gradient

K is hydraulic or capillary conductivity and

Ψ Capillary potential

K and Ψ depend strongly on the initial moisture content of the porous medium.

One dimensional capillary absorption can be described by non-linear diffusion equation as

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[D(\theta)\frac{\partial \theta}{\partial x} \right] \text{ ………………………. (Eqn. 2-5)}$$

where,

θ is water content of the material

D (θ) is a material property the unsaturated hydraulic diffusivity

Subject to a free reservoir boundary condition at x = 0 and uniform initial water content throughout this equation has a solution of the form

$$x(\theta, t) = \varphi(\theta)\sqrt{t} \text{ ……………………….... (Eqn. 2-6)}$$

where,
φ is a Boltzmann variable $x\sqrt{t}$

Integrating the above equation would give us the total amount of water absorbed as

$$i(t) = t^{0.5}\int_{\theta_0}^{\theta_s} \varphi d\theta = St^{0.5} \text{ …………………….. (Eqn. 2-7)}$$

where,

θ_s is the final/saturation moisture content of the material

θ_o is the initial moisture content of the material

S is the sorptivity

This forms the basis of defining the sorptivity of concrete considering that the water imbibes in one dimensional flow in proportion to $t^{0.5}$. Here i is the cumulative volume of absorbed liquid per unit area of inflow surface. Hall through his pioneering research demonstrated linearity in the plot between sorption per unit wetted surface area and square root of time and defined it as sorptivity [70]. Through experimental investigations a more general form of equation was evolved as

$$i = A + St^{0.5} \text{ .... (Eqn. 2-8)}$$

where,

A is a small constant that bundles together minor surface effects like rapid filling of open surface pores [69].

For this law of $t^{0.5}$ to hold true, the following conditions must hold true [71, 72]:

1. **Material:** The material must be homogenous on the scale of the penetration distance
2. **Sample geometry:** the capillary absorption flow must be normal to the inflow face and not be converging or diverging
3. **Test Procedure:** water must be freely available at the inflow surface and the gravitation effects must be apparent in the absorption process.

It is worth mentioning here that the dominant mechanism of ingress of water at relatively shorter periods (few hours), especially near partially saturated or unsaturated surfaces, in sorption, is defined by capillary pores and transport by capillary action [70, 73] while long term moisture movement is controlled by gel pores [74]. Sorptivity is a non-linear function of initial moisture content [75] of the material and the relationship can be given by the above stated equation and can also be expressed as a function of moisture content as [76]

$$S(\theta) = S_0\sqrt{(1-\lambda\theta_n}$$ …………………….. (Eqn. 2-9)

where,

S (θ) is the sorptivity coefficient at any moisture content θ, such that the normalized moisture content

$$\theta_n = (\theta - \theta_0)/(\theta_s - \theta_0)$$ ……………………. (Eqn. 2-10)

S_0 sorptivity at the initial moisture content

Due to the basic difference in the nature of absorption and the involved forces and mechanisms, the unsaturated flow theory is applicable for only shorter periods of time and even deviates for shorter time periods as is discussed in a latter section. To overcome this difficulty and to accommodate the differences in the nature of the water absorption in short and long term, a stretched exponential function has been found to describe moisture uptake in porous materials over an extended period of time. This empirical function which incorporates the stretched exponential function [77] to account for the crossover regime as:

$$i = \frac{W}{A} = C(1 - \exp(-St^{0.5} / C)) + S_g t^{0.5} + S_0 \text{ ………….. (Eqn. 2-11)}$$

where,

W is the volume of water absorbed

A is the exposed surface area

C is a constant that is related to the distance from the concrete surface over which capillary pores control the initial sorption

S_g (<< S) describes the sorptivity in smaller pores or the effects of moisture diffusion

2.9.2 Influencing Factors

(i) Surface tension (σ), viscosity (η) and density (γ) of the liquid decide the intrinsic hydraulic properties of concrete. Researchers have established that the sorptivity in concrete varies as $(\sigma / \eta)^{0.5}$ depending on the miscibility of the liquid under consideration with the water in the active material-concrete. A general equation is given as

$$S = (\sigma / \eta)^{0.5} S_i \text{ ……………………….. (Eqn. 2-12)}$$

(ii) Viscosity of a fluid falls more rapidly than its surface tension. A change in the temperature from 10 ^{o}C to 30 ^{o}C of water can cause the sorptivity value to increase by about 25 %.

(iii) The capillary absorption of a liquid by concrete depends on the microstructure. Within the microstructure are the important phases of the porous material called as concrete viz. the cement paste, the aggregates and the aggregate paste inter-phase. A detailed discussion is beyond the scope of this thesis.

(iv) The sorptivity is influenced by the initial moisture content as given by the equations in the previous section.

(v) The sorptivity of cement/sand mortars increases as the mixture becomes leaner. [71]

(vi) Compaction has a significant influence on the porosity and width of interfacial transition zone (ITZ). The porosity of the ITZ of conventionally vibrated concrete is affected by nature of vibration of concrete and affects its strength, permeability and hydraulic conductivity [78]. In addition to this, placing and compaction operations of concrete invariably result in bleeding and redistribution of aggregate. Research has found that the sorptivity of the more-porous top surface (laitance intact) has a relatively 55% greater co-efficient of sorptivity than the bottom surface [40].

(vii) The liquid transport properties of concrete are determined by the composite action of mortar matrix and the properties of coarse aggregate. If the coarse aggregate is of very low porosity and therefore essentially non-sorptive any liquid transport will occur mainly through the mortar matrix and vice-versa. Dense non-sorptive coarse aggregates will reduce the overall sorptivity of a concrete. Although the total liquid absorption may be very small, the liquid will be concentrated in the cement-containing part of the concrete where degrading reactions occur. It is also predicted theoretically that very porous lightweight aggregates produce an increase in the sorptivity of concretes, but this increase in the sorptivity is reduced when there is a strong contrast between hydraulic resistances of aggregate and matrix [79]. Basically the difference between in the pore structure of stone and cement paste is the existence of gel pores [80]. Further details of the analytical treatment of the subject matter are available in [81].

(viii) Concrete grade and specimen preconditioning influence Sorptivity significantly. Increase in grade of concrete (with a reduction in w/c ratio) leads to reduction in the sorptivity of concrete. The details of effects of specimen preparations are discussed in the chapter on materials and methods. Specimen size and coating do not influence Sorptivity [62].

2.9.3 A Critique on $t^{0.5}$ and Linearity of Plot: Anomaly

Some conflicting results are obtained from some of the experiments previously conducted concerning the time dependence of the total water uptake via capillary action. Instead of the standard $t^{0.5}$ behavior of simple capillary sorption theories other t^{α} behavior, also known as anomalous scaling, where $0.25 < \alpha < 0.5$ has been observed [82, 83]. It has been suggested that the anomalous scaling in concrete is the result of modification of the pore structure due to leaching [84] or further hydration as the water is absorbed. For instance, while hydration would reduce the typical pore size in the cement paste matrix, slowing the sorption of water, leaching opens up pores, making them larger and more connected such that capillary sorption is enhanced [74]. The linearity of this relationship was validated for fuel oil, [85] while in case of water the anomalous behavior was explained on the basis of phenomenon of new hydration, which takes place in the presence of water and causes an increase of effective grain size and tends to block the micro pores, consequently resulting into hindered water movement through concrete [86]. At the same time it should be stated that it has not been quantitatively well understood and demonstrated how such alterations of the pore structure affect a materials' sorptivity. Additionally, the dissolution of salts may reduce the rate of capillary sorption [87]. Finally as mentioned previously, moisture transport in concrete is a dynamic process involving moving water and evolving/live hydrating cement and depends on other factors as the degree of saturation and environmental conditions.

Considering other building materials like fired-clay brick and limestone, researchers have found that the wetting surface or the water advancing front actually does not progress as a function of $t^{0.5}$. This implies that the absorption process does not conform to the predictions of the theoretical analysis of one dimensional infiltration of these two materials. Unlike the previous researchers [88-90] who proved the validity of $t^{0.5}$ law for bricks and other masonry products used in building construction, latter researchers not only proved that the one-dimensional water infiltration scales in proportion to $t^{0.58}$ and $t^{0.61}$ in brick and limestone respectively, but also stated that the amount of absorbed water in initially overestimated by $t^{0.5}$.

In their classic reviews of this problem, Lockington and Parlange [cf. 91] and then Hall [cf. 69] addresses these issues. The summary of the paper by Lockington and Parlange is as follows:

1. Deviation from $t^{0.5}$ behavior is both short term and long term and can be largely attributed to the *chemo-mechanical* processes taking place, while the shortcomings in the experimental setup and design cannot be underestimated.
2. The anomalous long-term behavior of concrete sorption can be attributed to the chemo-mechanical changes in the form of hydration reaction with cement may tend to restrict the pore throats and affect the connectivity without significantly changing the material's total effective porosity.
3. The reduced anomaly is observed if the proportion of low density calcium silicate hydrate gel in the cement is reduced (ex. As in blended cement).

4. The deviation in the initial absorption is a manifestation of deviation from water flux-gradient proportionality and might occur If water behaved like a non-Newtonian fluid, in which case non-linear diffusion equation is proposed.
5. Considering the physics and chemo-mechanical behavior the authors came up with a $t^{0.57}$ for short term anomaly for brick and $t^{0.46}$ anomaly for blended Portland cement and proposed a generalized sorptivity and diffusion equations for both stationary and non-stationary media.

The paper by Hall is summarized as follows:

1. There is clear evidence of water sorptivity anomalies in cementitious materials and hence the equation given by Eqn. 2-8 may not strictly hold for concrete, even though a substantial amount of research exists to substantiate this.
2. In case of trapped air, it is evident that the water content near the inflow surface approached the volume fraction porosity of the material, but falls quite rapidly in the interior to a lower value which is close to capillary moisture content. Air is not trapped in the surface pores but air trapped near the surface is progressively released by diffusion of dissolved gases. This air diffusion process itself has $t^{0.5}$ kinetics.
3. Temperature dependence of sorptivity can directly be predicted from the temperature dependence of the surface tension and viscosity.
4. On longer timescales the water absorption profiles fall below the $t^{0.5}$ line and this behavior can be described as sub-diffusive arising from a strong physiochemical interaction between the pore fluid and the porous solid.

2.10 Mix Proportioning Strategies

The primary differences in proportioning RCC pavement mixes and conventional pavement concrete are as follows:

1. RCC is generally non air-entrained.
2. RCC has lower cement content.
3. RCC has lower cement paste content.
4. RCC generally requires a larger fine aggregate content in order to produce a combined aggregate grading that is well-graded and stable under the vibration of a vibratory roller.
5. RCC generally uses NMSA 19mm in order to produce a non-segregating mixture with a relatively smooth surface [2, 4].

Several methods have been used to proportion RCC pavement mixtures. These vary primarily by the application and the local practice used. These methods can be placed in two broad categories [2, 4]:

1. Proportioning by use of concrete consistency tests
2. Proportioning by soil compaction tests

Other methods available for proportioning are considered beyond the scope of this work. Since soil compaction tests' method was used in proportioning the mixes used for this research, therefore a summary flow chart exemplifying the design philosophy is shown in Figure 18. Note that before accepting a mix, strength and durability specs are to be satisfied.

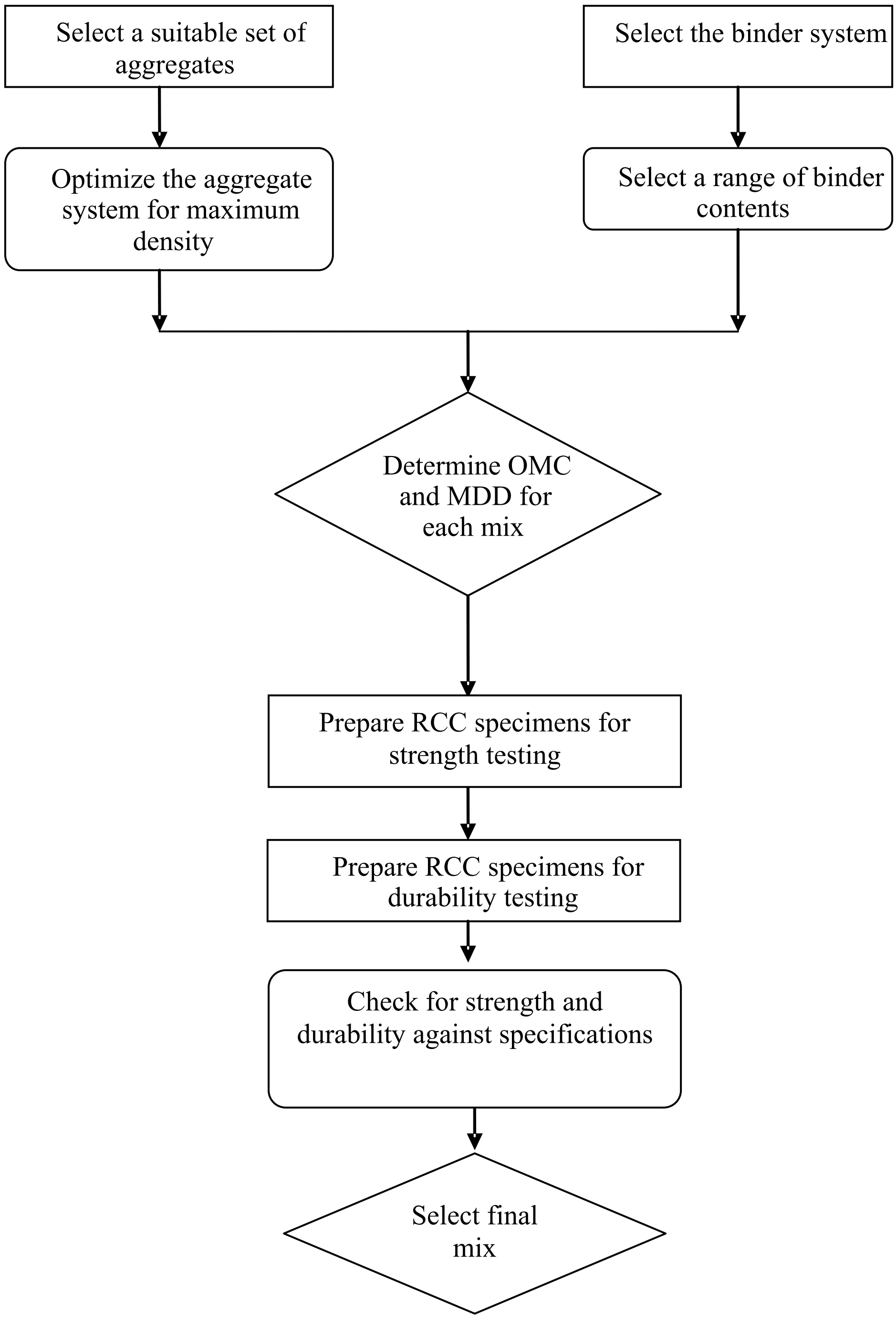

Figure 18 RCC mix proportioning: Soil analogy method

2.11 Freeze-Thaw Resistance

2.11.1 General

Freeze-thaw damages may manifest themselves in the form of surface scaling and/or internal cracking. The process of surface scaling may occur on both horizontal and vertical surfaces, but mainly where *water exists* in contact with concrete and can *penetrate* inside the concrete. The process of internal cracking is less recognized and/or observed in field. In addition to this, these processes can join hands with other deterioration mechanisms leading to more catastrophic damages than can be anticipated. Freezing of concrete is a gradual process and concrete depending on its capacity, generates its own barrier system and defense mechanism to counteract the damaging effects of freezing. It is also important to mention that the internal *microconcrete-microclimate* reacts in its own way and it is difficult, if not impossible to fully characterize its response to the external macro-climatic effects. Concrete for this matter may be conceived as a sieve like material that has a series of distinct sizes of sieve openings, each responding in its unique way to the process of freezing of water.

Table 9 Pore size classification and nature of water [92]

Pore class	Upper R_h	Kind of water	Filled by
Micro gel pores	1 nm	structured	Sorption (<50 RH)
Meso gel pores	30 nm	prestructured	Vapor condensation (50-98 % RH)
Micro capillaries	1 µm	bulk	Suction (no max. height reached)
Meso capillaries	30 µm	bulk	Suction (max. height reached after minutes to some days)
Macro capillaries	1mm	bulk	Suction . (max. height reached below 1 min.)

Note: R_h means hydraulic radius

For understanding the nature of concrete-porosity, which prima-facie, determines the response of concrete to such action is of vital importance. Additionally an understanding of the freezing behavior of water in this porous material is crucial. Table 9 gives a general classification of pore size and pore water uptake in concrete.

Water is taken up by the concrete structure in two ways:

1. adsorption and capillary condensation and
2. capillary suction

The adsorbed and condensed water either is structured and does not freeze normally or is pre-structured with a depressed freezing point below -20 °C. Water which is sucked up is at least partially freezable depending on the minimum temperature. In addition to this, deicing chemicals are transported with the water into concrete structure. Moreover, this hydraulic load undergoes thermal expansion approximately 10 times larger than the expansion of ice. Together with the freeze-thaw hysteresis this leads to a pumping effect. If there is an external reservoir, additional water saturation is observed after a freeze-thaw cycle. The water uptake is much larger than the usual capillary suction at room temperature. Finally water transport takes place within the microstructure of concrete. It is generated by the changed surface interaction after ice is formed. This is connected with both changes of chemical potential and pressure differences. The change in the chemical potential leads to desiccation of small pores and a water uptake of the larger ice filled pores combined with shrinkage and swelling. On the other hand the pressure differences leads to contracting forces in small pores and either to smaller contracting forces or even expansion in the larger pores depending on boundary conditions. Therefore the transport phenomena during freeze and thaw cycle leads to an additional water uptake and to microstructural changes and damages [92].

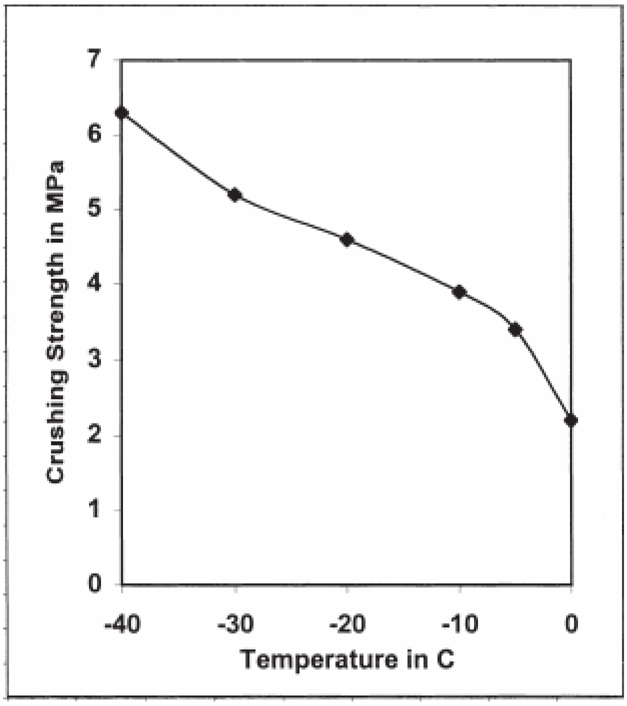

Figure 19 Variation of strength of ice with temperature [93, 94]

It is important to note that the freezing of water is accompanied by an increase in volume by 9%. Ice has both compressive and tensile strength in short term, but has none in long term. This means that ice is a *viscoelastic* material in the long term. Figure 19 represents the variation of crushing strength of ice with temperature. Table 10 shows the effects of short- and long term loading on the strengths of ice. The strength of ice is also affected by the presence of dissolved materials; some of the solutes increase the strength and other decrease it [95].

Table 10 Loading and compressive strength of ice [96]

Temperature (°C)	Uniaxial strength (MPa)			
	Short term		Long term	
	Compressive	Tensile	Compressive	Tensile
-3	1.6-2.0	1.0-1.2	0	0
-10	3.2-4.0	1.7-2.0	0	0

Another aspect of Freeze-Thaw resistance of concrete is its compressive strength response to lower temperatures. The compressive strength of frozen concrete increases with the increasing water content and with decreasing temperature. A detailed description of these phenomena is available in the literature [97]. A saturated concrete on the other hand shows a loss of strength when measured at room temperature, compared to its virgin strength, at every freeze-thaw cycle [98], whereas a concrete dried at 85% relative humidity shows no such loss in strength [99]. Thus only saturated or nearly saturated concrete suffers internal damage during freezing even though strength measured on frozen concrete does not reveal it. Similarly the tensile strength of a frozen concrete also increases with increasing moisture content and lowering temperature between 0 and about -60°C. Finally a saturated concrete also loses its tensile strength during every freeze-thaw cycle.

To cause damage to a freezing concrete by an internally generated pressure, its magnitude needs to be about two times the tensile strength of the frozen part of the concrete [10]. The tensile strength of a reasonable quality saturated concrete is about 2.5 MPa at room temperature. This means the tensile strength of the same concrete will be about 4 MPa at -10°C and 6 MPa at -20°C. It is, however, seldom known exactly at what temperature of the freezing cycle of a concrete damage occurs. The damage-producing pressure can therefore be between 8 and 12 MPa or approximately 10 MPa. The Freeze-Thaw damage mechanisms viz. hydraulic pressure theory [100], osmotic pressure theories [101-103] are considered beyond the scope of this work.

The role of aggregates in the F-T resistance is important as they occupy a major part of the concrete matrix, a three phase system (viz. cement paste, aggregates and aggregate-paste inter-phase). An aggregate by itself will not be vulnerable if it has low porosity, or if it's capillary system is interrupted by a sufficient number of macrospores.

However an aggregate particle in concrete can be considered as a closed container, because the low permeability of surrounding hardened cement paste will not allow the water to move sufficiently rapidly into air voids. Thus an aggregate particle saturated above 91.7 % will, on freezing, destroy the surrounding mortar [104].

2.11.2 F-T Resistance of RCC

2.11.2.1 The Macro- and Micro- structure

Dry concretes like RCC can have an internal structure very different from that of normal concretes; it is not clear that the theories related to frost action which are valid for normal concretes are also applicable to dry concretes [105]. RCC as stated previously has a very dry/stiff consistency, which certainly is a demand of the molding operation and is manifested in the form of low cement pastes with just the right quantity of water for achieving the right degree of compactness. Thus unlike the CVC which to a great extent has a self-consolidating consistency, RCC requires additional compaction energy to get molded.

The microstructure of RCC plays a crucial role in deciding its physical response to different kinds of loadings viz. mechanical, hydraulic, etc. What further differentiates RCC from CVC is the presence of compaction voids. Practically speaking concrete is primarily vibrated to expel all the entrapped air. Due to the stiffer consistency of RCC, it is not only difficult, but also impossible to expel a comparable amount of entrapped air, which exists as compaction voids in RCC. The amount and nature of compaction voids principally depend on the cementitious composition and quantum, consistency of concrete, aggregate packing and shape.

Another deviation from CVC is in the form of relative heterogeneity of cement paste. Due to lower consistency of the mix, it is difficult to disperse the cement grains properly [105]. Additionally the aggregate content of the mix is relatively higher. Consequently, the RCC could be perceived as a mix composed of aggregate skeleton coated with a thin layer of dry cement paste. If the grading of these particles is optimized, the number of compaction voids can be very low; but if it is not, the number of compaction voids can be very high. In certain extreme cases, the compaction voids can even form a continuous network [106].

Due to the compaction process, dry consistency of cement paste and rigid aggregate content (which would resist shrinkage), it is possible that shrinkage in the paste creates much more cracking than in normal concretes due to higher restraining affect of the aggregates. In addition to this, the heterogeneity of cement paste, RCC usually has a more permeable structure than the CVC. This can facilitate the movement of water to the air voids during freezing, but the areas in the paste with a higher volume fraction of water are obviously more susceptible to frost action [106]. Another important feature is the presence of numerous porous and cracked interfacial zones. It has been hypothesized that the high stiffness of RCC mixtures favors the formation of these porous interfaces. Due to this high stiffness, paste movements around the aggregate particles are limited during mixing. The water film at the wet aggregate surface can not adequately be distributed throughout the mixture, thus increasing the porosity at the interface. Even high-energy mixers are simply not efficient enough to remove the water film at the aggregate surface [107].

2.11.2.2 Air Entrainment and Air Void System

The total air content of the concrete is not the most significant parameter with respect to the protection of the concrete against frost damage [108]. Conventionally entrained air is characterized as a parameter indicative of the F-T resistance of concrete and we have calibrated our systems and concretes on these measurements.

Air bubbles can only be formed in concrete mixture if there is sufficient amount of water, since each bubble has to be surrounded by a film of water [109]. In dryer mixes, a sort of kneading action takes place during the formation of these air bubbles. Other than the materials, the mixer energy place a crucial role; higher mixing speeds giving higher air contents; longer mixing time leading to a marginal increase with increasing time leading to decrease in the air content. Vibration on the other hand reduces the air content, with larger bubbles lost most easily [108]. In drier concretes, entraining air is only possible if the mixing sequence is modified in such a way as first mix the cement, the water and the air-entraining agent with only a fraction of aggregate. Once the mixing has allowed the formation of a sufficient volume of air voids then the rest of the aggregates can be added [110].

In a majority of laboratory and field studies [111-115] it was observed that a substantial amount of entrapped air in the form of compaction voids was observed, while the entrained air was merely formed. Use of counter current pan mixer has been found to be of some help in entraining the air in RCC [116]. In one of the investigations [117], the air void characteristics of the RCC mixtures showed a very low (0.1-0.6 %) spherical air bubbles' content; a relatively low spacing factor (84-169 μm) and the specific surface were relatively much lower (117-21.9 mm^{-1}). These observations lead to conclusions that the voids resulting from compaction exist in the concrete matrix in relatively much higher quantities and are relatively larger. In a survey of RCC pavements constructed during

1976-1985 [118] the frost durability of RCC tested was directly related to the air void spacing factor. This is shown in Figure 20. Since no significant amount of air bubbles were found during the microscopic examinations, the results of these tests show that the compaction air void system can in *certain cases* offer an adequate protection against frost action. Contradictory to this, some field performance observations of existing pavements in British Columbia [119] and New Hampshire [120] have tended to confirm that non-air-entrained RCC can be resistant to natural F-T cycles in certain regions, although it is not evident that this will remain true for all the regions. It is important to note that the samples taken from the pavements in British Columbia had shown contradictory behavior in lab testing in accordance with ASTM C666 test. This lab-field discrepancy was also substantiated in another RCC study [121].

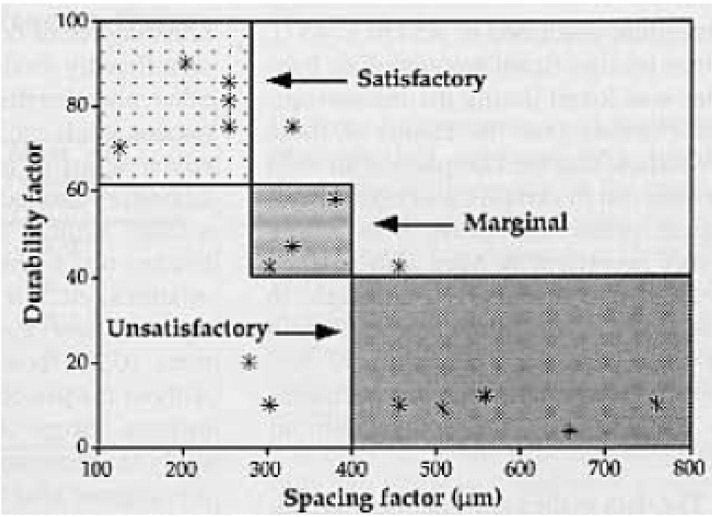

Figure 20 Spacing factor and durability of RCC [118]

In summary, with regard to internal cracking, the compaction voids can offer the same protection as the air bubbles in normal air-entrained concrete. It is further possible that the higher permeability of the dry concretes has a positive effect because it helps to reduce the internal pressures due to the movement of water to the air voids during freezing. However the compaction voids do not always offer a sufficient protection [105]. The best indicator of RCC durability is its performance in the field [2].

Synopsis

On the basis of the conducted literature review the following scope of work was identified, taking cognizance of the available resources:

1. *RCC manifests comparable or better mechanical characteristics when compared with CVC at same cement content. Taking into account the cost savings achieved by using RCC as a construction material and method, RCC presents itself as a comparable or superior material. A wide range of applications for RCC for pavement applications exist, but are more often than not limited due to incomplete comprehension of the competence of this material in the form of a unifying study. Thus there is a scope for exploring the possibilities of applications of RCC in pavements. A study understanding the variations in the mechanical strength of RCC mixes over a wide range of cement contents can thus be conceived to fulfill this objective.*
2. *Transport of water in concrete is an important phenomenon that by and large is responsible for carrying the agents of distress in concrete, both physical and chemical. An incomplete understanding of this subject exists in literature for CVC, but there is no research that addresses the water transport behavior of RCC. Although a limited number of studies exist on the permeability aspects of RCC, there are no studies that characterize the sorptivity and/or drainage-desorptivity*

of RCC. Further to this, the sorptivity behavior of RCC top and bottom surface are going to be distinct due to the nature of layer formation during compaction. This influence of the location of concrete in a layer in response to the water transport by capillarity can thus be studied to understand the most-damage susceptible portion of a layer of RCC.

3. *F-T durability of RCC for wearing course applications has been studied along with some studies on the comparative behavior of air-entrained and non air-entrained RCC. A comprehensive comparative study characterizing a wide range of cement contents has not been conducted till date. Thus there is a need to study the comparison of the air-entrained and non air-entrained concrete and understand the variations in the strength, bulk properties and F-T resistances.*
4. *Bulk properties like water absorption and permeable voids content will help understand and quantify the amount of voids and their influence on the water transport properties of concrete. There is no study available in the literature that covers these aspects either of CVC or RCC. A comprehensive study of this kind will help understand the variations in the bulk properties of RCC with the cement contents.*

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3. EXPERIMENT FORMULATION: MATERIALS AND METHODS

Summary

This chapter describes the material, methods and the sampling plan adopted for the research. At the onset this chapter describes conceiving of the experimental plan and the sampling scheme for the study. Later to this, the materials used for the experimental work are described in detail. Properties of cement, aggregates, admixtures and water are descried. Subsequently a summary of the significant test methods used for this study are described. Certain non-standard methods are used in this research and are explained in greater detail.

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3.1 Introduction

After identifying and defining the research need statement and planning the study a detailed research plan was prepared. Selection of appropriate parameters that will help realize the defined objectives followed the planning stage of the study. The complete investigation was conceived in two phases viz. LPI and LPII. The cement content range of the mixes was from 100 kg/m^3 to 450 kg/m^3. Phase-I consisted of all the mixes in the above range of cement contents in steps of 50 kg/m^3. All the mixes in this phase were non air-entrained and incorporated water reducer in order to enhance the consistency and plasticity of the mixes. Phase II mixes consisted of selected mixes to cover the entire range of cement content. All the mixes in this phase were air-entrained and incorporated the same quantities of water reducer in order to have a common basis of comparison between the two phases. Thus the number of variables were viz. cement content (hence the w/c ratio and mechanical strength), chemical admixtures, sorptivity test conditions. Since no mixes without any admixtures were cast, therefore mixes with water reducing admixtures (from LPI) served as control mixes.

The test method selection formed the key part during this phase. Considering the limited resources, the test matrix was designed such that with minimum number of tests the predefined objectives would be achieved. The fresh properties of the mixes were characterized using the VBT and OMC-MDD parameters. OMC-MDD plots were generated by conducting a series of trials of the optimized grading curves with different cement contents. The method of compaction utilized was the compacting hammer method so that the densities achieved during final mix casting matched with densities achieved during the preliminary stages of mix optimization. Compressive strength was then measured at the ages of 7 and 28 days. Bulk properties like the water absorption, boiling voids and densities were determined on suitably formed specimens. The specimen formulation is described in latter section. Special beams were cast for extracting specimens for cyclic F-T testing.

The next phase of the study was material selection. It was decided that the study shall be confined to ordinary Portland cement (O.P.C.) and would not include any supplementary cementitious materials. Locally available aggregates with nominal maximum size (NMS) of 19 mm were chosen. The coarse aggregate used was limestone available in Ames. Fine aggregate consisted of siliceous river sand. It was decided that the chemical admixtures shall be used for enhancing the plasticity and cohesion of the mixtures and to test the possibility of entrainment of air in RCC. To realize these objectives two distinct objectives were chosen viz. a water reducer and an air entraining admixture.

3.2 Statement of Sampling

The final materials', specimens' and test matrices are shown in Tables 11 and 12.

Table 11 Materials' matrix for the investigations

Details	L-PI	L-PII
OPC	X	X
Limestone	X	X
Natural sand	X	X
Water reducer	X	X
Air entraining admixture	NA	X
Specimen matrix		
No. of mixes	8	4
No. of cylinders for M-D curves	120	60
No. of cylinders for testing	112	56
No. of beams	8	4
No. of cores for F-T and comparison	39	20
No. of slices for sorptivity	48	24
No. of cores for sorptivity	24	12
No. of slices for bulk properties	48	24
No. of cores for bulk properties	24	12
Total specimens	431	216

Table 12 Test matrix for the investigations

Test details	No. of specimens/test	No. of samples		Total
		L-PI	L-PII	
Compressive strength-7 days	2	8	4	24
Compressive strength-28 days	2	8	4	24
Voids by boiling water method	9	8	4	108
Sorptivity and desorptivity	9	8	4	108
F-T resistance	4	8	4	48
SEM-air void analysis	4	4	4	32
Total	24	48	24	344

3.3 Materials

3.3.1 Ordinary Portland Cement

Table 13 Properties of cement

Property	Unit	Value	Limit
Physical Properties			
325 μm passing	(%)	91.30	--
Blaine fineness	(m^2/kg)	374	Min. 280
Vicat initial setting time	(min)	94	Min. 45
Vicat final setting time	(min)	198	Min. 275
Normal consitency	(%)	25.70	--
Air	(%)	7.40	Max. 12
Compressive strength			
1-day	(MPa)	16.30	--
3-day	(MPa)	27.90	12.00
7-day	(MPa)	37.03	19.00
28-day	(MPa)	47.10	--
LOI	(%)	1.72	Max. 3
Chemical Composition			
Silicon Oxide, SiO_2	(%)	20.35	--
Aluminum oxide, Al_2O_3	(%)	5.13	--
Ferric oxide, Fe_2O_3	(%)	2.14	--
Calcium oxide, CaO	(%)	64.34	--
Magnesium oxide, MgO	(%)	1.93	Max. 6
Sulphur trioxide, SO_3	(%)	2.95	Max. 3
Sodium oxide, Na_2O	(%)	0.21	$Na_2O + 0.6K_2O$
Potassium oxide, K_2O	(%)	0.44	Max. 0.6
Bogue's Composition			
Tricalcium silicate, C_3S	(%)	61.39	--
Dicalcium silicate, C_2S	(%)	12	--
Tricalcium aluminate, C_3A	(%)	9.96	--
Tetracalcium aluminoferrite, C_4AF	(%)	6.51	--

The O.P.C. used for these series of investigations was ASTM Type I cement manufactured by Holcim. The physical properties, chemical composition and Bogue's composition are as per Table 13.

3.3.2 Mineral Aggregates

The nominal maximum sizes of the aggregates were kept as 19 mm considering the workability aspects of the concrete and their application for pavement purposes. Two types of coarse aggregates were used in the investigations with the objective of fulfilling the overall goals of the project. Fine aggregate were natural river sand collected procured from a local quarry. The nominal maximum size of the fine aggregate was 4.75 mm. Table 14 shows the particle size distribution of the individual fractions of the aggregates, while Table 15 gives the bulk properties of aggregates.

Table 14 Particle size distribution of aggregates

Sieve	Cumulative Percent Passing (%)		
(mm)	CA-I	CA-II	FA
25.000	100.00	100.00	100.00
19.000	100.00	92.70	100.00
12.500	99.96	31.55	100.00
9.500	99.41	3.84	100.00
4.750	6.91	0.74	97.82
2.300	2.50	0.74	82.35
1.180	0.58	0.74	60.37
0.600	0.58	0.74	33.96
0.300	0.58	0.74	9.83
0.150	0.58	0.74	0.78
0.075	0.58	0.56	0.34
F.M.	5.89	6.99	3.15

In case of limestone the aggregate fractions were separated into two fractions viz. 19.0 to 9.5 mm and 9.5 to 2.36 mm and were then recombined to formulate the combined aggregate gradings for individual mixes. The combined particle size distributions for different mixes, accommodating the amount of fines were obtained using the formula

$$CPP = (d/D)^{0.45} \times 100 \quad \text{(Eqn. 3-1)}$$

The fines content of the individual mixes were adjusted depending on the amount of cement content in the mixture.

Table 15 Bulk properties of aggregates

Aggregate Property	Coarse	Fine
Size fraction	4.75 - 19 mm	0 - 4.75 mm
Specific Gravity	2.537	2.642
Water absorption (%)	3.4	1.05
Los Angeles Abrasion (%)	44	NA

3.3.3. Chemical Admixtures

Two types of chemical admixtures were used for these trials. A water reducing admixture specifically manufactured for dry paving concretes and an air entraining agent. The relevant properties are summarized in Table 16. In addition to this Figures 21 and 22 show the infrared (IR) scans of these admixtures.

Table 16 Properties of chemical admixtures

Property	Condition	Water reducing admixture	Air entraining agent
pH	25 ºC	6--11	10--12
Specific Gravity	25 ºC	1.16-1.21	1.005-1.025
Residue by oven drying (%)		41.5-51.5	5.9-7.55
Chloride content (%)		< 0.2	< 0.1

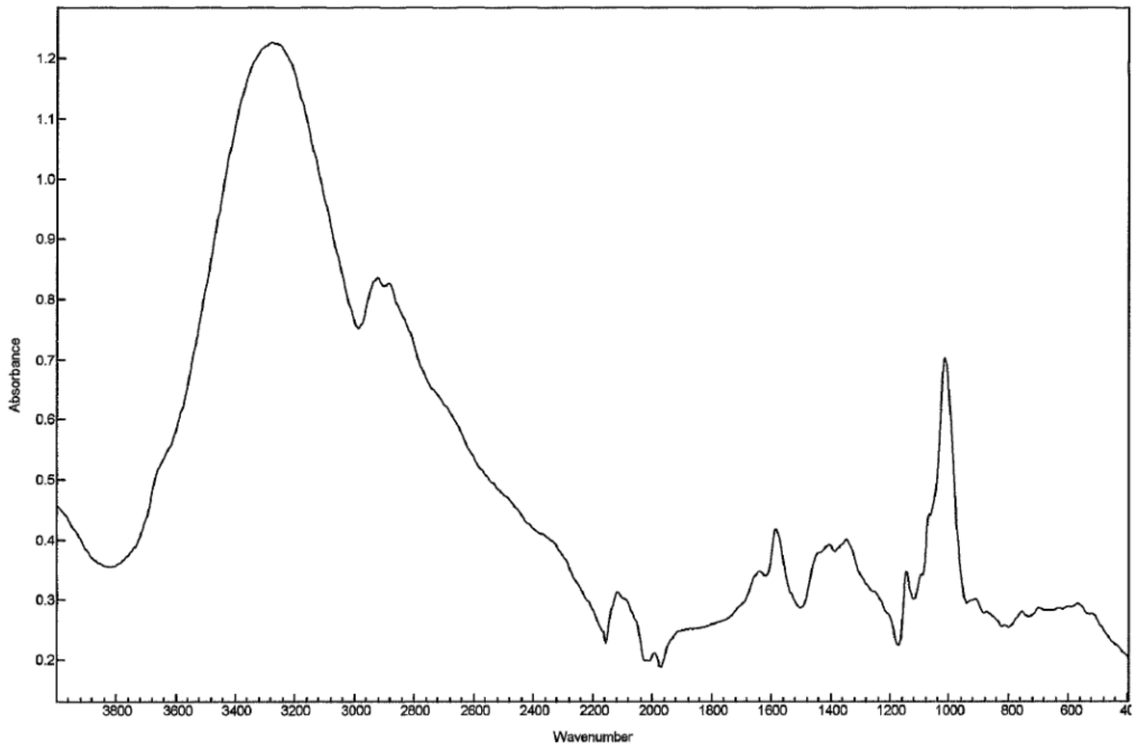

Figure 21 IR Scan for the water reducing admixture

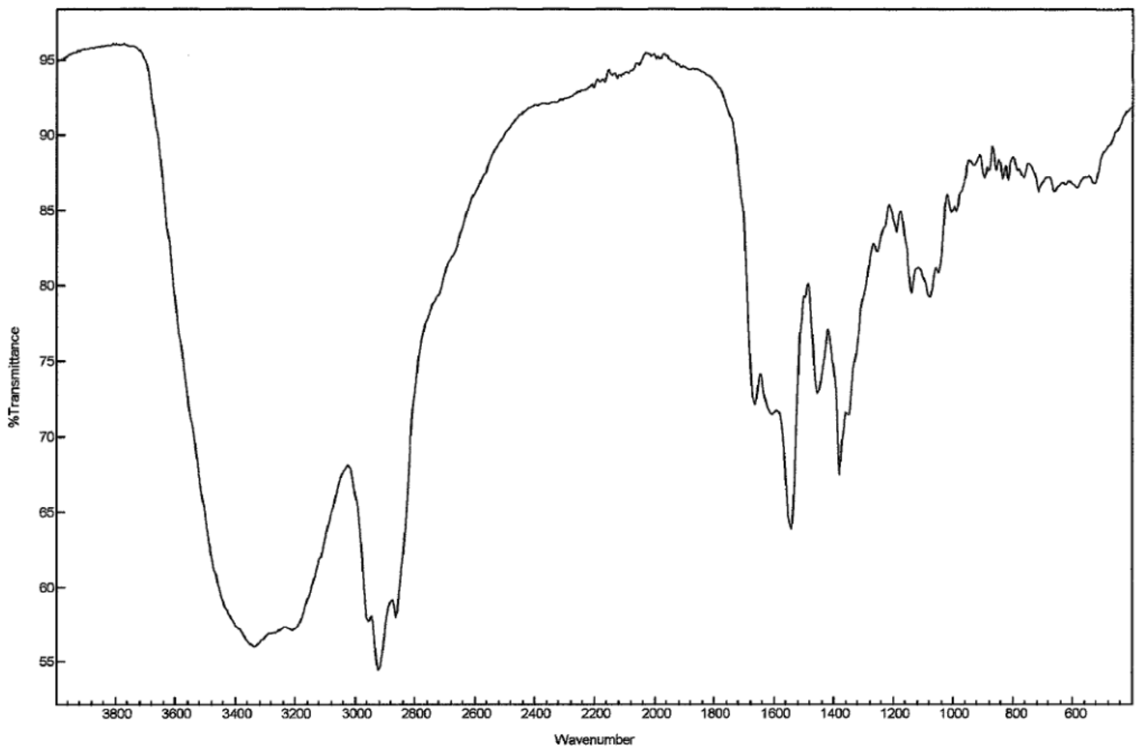

Figure 22 IR scan for Air entraining agent

3.3.4. Water

Tap water was used for concrete mixing.

3.4 Test Methods

3.4.1 Statement for Selection of Test Parameters

With an array of test methods available for testing engineered concretes and concrete making materials, it is more often than not a set of choices at the hands of the researcher to choose the most practical ones to realize the objectives of a test program. Considering the available resources, the test variables were chosen to suit the requirements of the study in order to derive some meaningful results. Table 17 shows the correlations of test objectives, test parameters and results.

Table 17 Test selection criteria

Objective	Parameter	Variable	Constant	Outcome
Strength evolution with change in the cement factor	Compressive strength and w/c	Cement content	Consistency	Objective-1
Role of compaction voids in F-T resistance	Permeable voids, F-T, water absorption	Depends on No. 1	Compaction energy	Objective-2
Nature of sorption and desorption behavior	Sorption profiles and desorptivity	Depends on No. 1	Preconditioning	Objective-3
Distribution of air voids	Void characteristics	Depends on No. 1	Age and admixture dosage	Objective-4

3.4.2 Test Methods

All the usually conducted preliminary materials' tests were performed in accordance with the relevant ASTM standards. A summary of the tests and test methods are summarized in Table 18.

Table 18 Standards for materials' testing

Material	Test	Test Standard
Aggregates	Particle size distribution	ASTM C 136
	Specific Gravity	ASTM C 127 and C 128
	Water absorption	ASTM C 127 and C 129
	Abrasion resistance	ASTM C131
Cement	Physical and chemical properties	ASTM C150
Chemical admixture	Physical and chemical admixture	ASTM C494, ASTM C260
Concrete	Vebe consistency	ASTM C 1170
	Compressive strength	ASTM C39
	Freeze-Thaw resistance	ASTM C666
	Water absorption	ASTM C642
	Sorptivity	ASTM C1585
	Desorptivity	No standard available
	Permeable voids content	ASTM C642
	Air void distribution	ASTM C457

3.5 Tests Method Statements

3.5.1 Concrete Mixing: A Critical Factor

The mixing of dry concretes like RCC acts as an influencing factor in deciding the some of the properties of concern in this study. This involves mixing sequence, mixing time and the mixing energy that is provided to the concrete. The mixing sequence as such influences the rheology and cohesion of the mix. Different researchers have used different methods for mixing concrete and the significant ones are briefed in Figure 23. Considering the wide range of cement contents used in these investigations and tilting lab mixer the following mixing sequence was used for mixing:

1. Full quantities of cement, half the quantity of fine aggregates, full quantity of chemical admixtures and three fourths quantity of water were mixed together for three minutes.
2. The mixer was then stopped for 1 min and allowed to rest.

3. At the end of this time, the remaining fine aggregate and coarse aggregates were added and the mixing was done for 3 min.
4. The mix was then allowed to rest for 2 min and was finally mixed for 2 min, before starting any tests.

<table>
<tr><td colspan="2">Time</td><td>Marchand, et.al.</td><td>PCA-RD135</td><td>ASTM C192</td><td>Ragan, et.al.</td><td>Houhanou, et.al.</td></tr>
<tr><td>Min</td><td>Sec</td><td>[1]</td><td>[2]</td><td>[3]</td><td>[4]</td><td>[5]</td></tr>
<tr><td>0</td><td>0</td><td rowspan="3">Mix cement+sand</td><td rowspan="3">Starting of mixer</td><td rowspan="5">CA + Partial water with admixtures (WR + AEA)</td><td rowspan="5">Cement + FA + Water + AEA and mix for 2 min</td><td rowspan="4">Mix FA + CA for 1.5 min</td></tr>
<tr><td></td><td>30</td></tr>
<tr><td>1</td><td>60</td></tr>
<tr><td></td><td>90</td><td>WR + partial water</td><td rowspan="2">Dry mixing of aggregates and cement/binders</td></tr>
<tr><td>2</td><td>120</td><td rowspan="6">CA + AEA + remaining water</td><td rowspan="3">Add AEA diluted in 1/2 water</td></tr>
<tr><td></td><td>150</td><td rowspan="4">Addition of water and diluted water reducer and AEA and mixing</td><td rowspan="2">Add cement + sand + reamaining water</td><td rowspan="2">Add CA and mix for 1 min.</td></tr>
<tr><td>3</td><td>180</td></tr>
<tr><td></td><td>210</td><td rowspan="6">Mix for 3 min.</td><td rowspan="6">Cover and rest for 3 min</td><td rowspan="4">Add cement/binder and mix for 2min</td></tr>
<tr><td>4</td><td>240</td></tr>
<tr><td></td><td>270</td><td rowspan="14"></td></tr>
<tr><td>5</td><td>300</td><td rowspan="13"></td></tr>
<tr><td></td><td>330</td><td rowspan="6">Add remaining 1/2 of the water and mix for 3 min</td></tr>
<tr><td>6</td><td>360</td></tr>
<tr><td></td><td>390</td><td rowspan="6">Cover the mixer and rest for 3 min</td><td rowspan="4">Open and remix for 2 min</td></tr>
<tr><td>7</td><td>420</td></tr>
<tr><td></td><td>450</td></tr>
<tr><td>8</td><td>480</td></tr>
<tr><td></td><td>510</td><td rowspan="6"></td><td rowspan="6"></td></tr>
<tr><td>9</td><td>540</td></tr>
<tr><td></td><td>570</td><td rowspan="4">Open the cover and remix for 2min.</td></tr>
<tr><td>10</td><td>600</td></tr>
<tr><td></td><td>630</td></tr>
<tr><td>11</td><td>660</td></tr>
</table>

Figure 23 Mixing methods for RCC

3.5.2 Moisture-Density Plots

The following procedure was followed for casting of concrete cylinders:

1. Initially the tare weights of plastic cylinders were measured along with their caps.
2. After mixing the concrete, it was compacted in the cylinders using the standard procedure outlined in the relevant standard. The hammer, sleeve and a cylinder are shown in Figure 24.
3. The time of compaction per layer was 45 ± 5 s and each cylinder was compacted in three equal lifts.
4. At completion of compaction the final layer, the top surface of the cylinder was finished with a trowel.
5. The cylinders were again weighed along with their caps to find the fresh density of compacted concrete.
6. Mixes with different moisture contents were caste until 4-5 points with different moisture contents and fresh densities were obtained. One such set of mixes are shown in Figure 25.
7. A concrete quantity of 2000 ± 100 g was kept in the oven at 105 ± 5 °C until constant weight was achieved. The difference between the initial and the final masses was used in calculating the moisture content of concrete.
8. Simultaneously three cylinders were kept in the oven for at least 96 hrs after demolding them to get the moisture contents from the compacted cylinders. A set of such cylinders are shown in Figure 26.

Figure 24 Compacting hammer, steel sleeve and a cylinder

Figure 25 Mixes at different moisture contents

Figure 26 Oven drying of cylinders for moisture content determination

For casting the beam specimens for extracting cores for F-T testing, the following procedure was adopted:

1. A quantity equivalent to volume of the beam mold and calculated from the fresh density of concrete cylinders was weighed out after mixing the concrete.
2. The compaction energy was similarly calculated for the beam specimens and the compaction time per layer was decided.
3. Subsequent to this the beams specimens were then caste in 4 equal layers as sown in Figure 27. Before casting a subsequent lift of concrete, the concrete was scrubbed for getting a rough texture so that a better bond between the two layers could be obtained.

Figure 27 Casting sequence of beam specimens for F-T samples

3.5.3 Sorptivity and desorptivity

3.5.3.1 Sample Preparation

Samples were prepared by cutting the concrete cylinders using diamond impregnated saw. For understanding the nature of capillary suction in different modes of absorption and to simulate the capillary action taking place in the pavement sections, three different kinds of specimens were prepared. This has been schematically shown in Figure 19. Table 3-6 shows the specimen dimensions and other characteristics

Table 19 Dimensions of sorptivity samples

SN	Portion	Coating	Dia. (d) (mm)	Height (t) (mm)	t/d	SA (mm^2)	V (mm^3)	SA_e (mm^2)	SA/V (mm^{-1})	SA/V (cm^{-1})
1	Top (T)	C	100	50	0.5	31429	392857	7857	0.08	0.8
2	Middle (M)	T+B	100	100	1.0	47143	785714	31429	0.06	0.6
3	Bottom (B)	C	100	50	0.5	31429	392857	7857	0.08	0.8

Due to time constraints of this study, the sorptivity samples were drawn out of curing room at the age of 14 days. Preconditioning was done by keeping these samples in oven at 50 ± 2 º C for 3 days and then in sealed containers for next 21 days. To measure relative amount of drying of specimens, equivalent specimens were kept in oven for 24 days at 50 ± 2 º C. This oven drying was used as reference drying. The densities obtained from these specimens were then utilized in calculating the desorption ratios. It is hereby assumed that there will be no further loss of moisture from the specimens after the age of 24 days. Two types of desorption ratios and a dryness ratio are defined and introduced. Subsequently sorptivity values for all the mixes were measure for 15 days or 366 hrs.

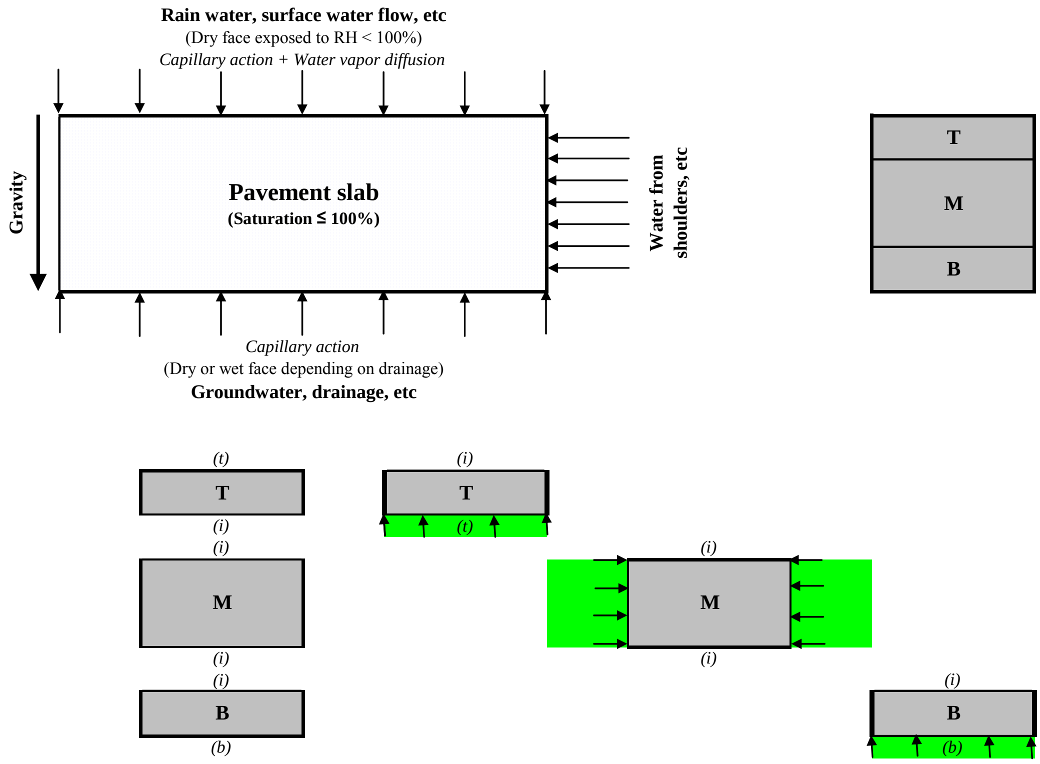

Figure 28 Simulation of sorptivity specimens with actual pavement

3.5.3.2 Significance of Sample Preparation

Table 20 Effects of preconditioning of specimens on sorptivity

SN	Condition	Effects	Remarks
1	Drying at 105 °C	• Alteration of pore structure • High sorptivities	6, 2, 8
2	Test under pressure	• Increases Sorptivity	2, 9
3	Thin Slices over full specimens	• Higher sorptivities	12, 8
4	Specimens coated while drying	• Higher sorptivities unless done for longer periods	10, 12
5	Short curing period	• Higher sorptivities and low duration of linearity	11

Dias recommends moderate degree of oven drying (ex. 3 days at 50 °C), so as to increase the sensitivity of the Sorptivity test without significantly reducing its discriminatory power. It is further recommended that the curved sides should be coated, in order to ensure uniaxial flow, and to reduce the artificially excessive porosity at cast concave curved surfaces due to reduced aggregate packing. Figure 29 shows the actual sorptivity specimens and coating applied specimens before testing. Several authors have tried several preconditioning methods for measuring the sorptivity of concrete and the salient ones are reported in Figure 30 and summarized in Table 20. Actual samples are shown in Figure 31.

Figure 29 Sample coating for sorptivity samples

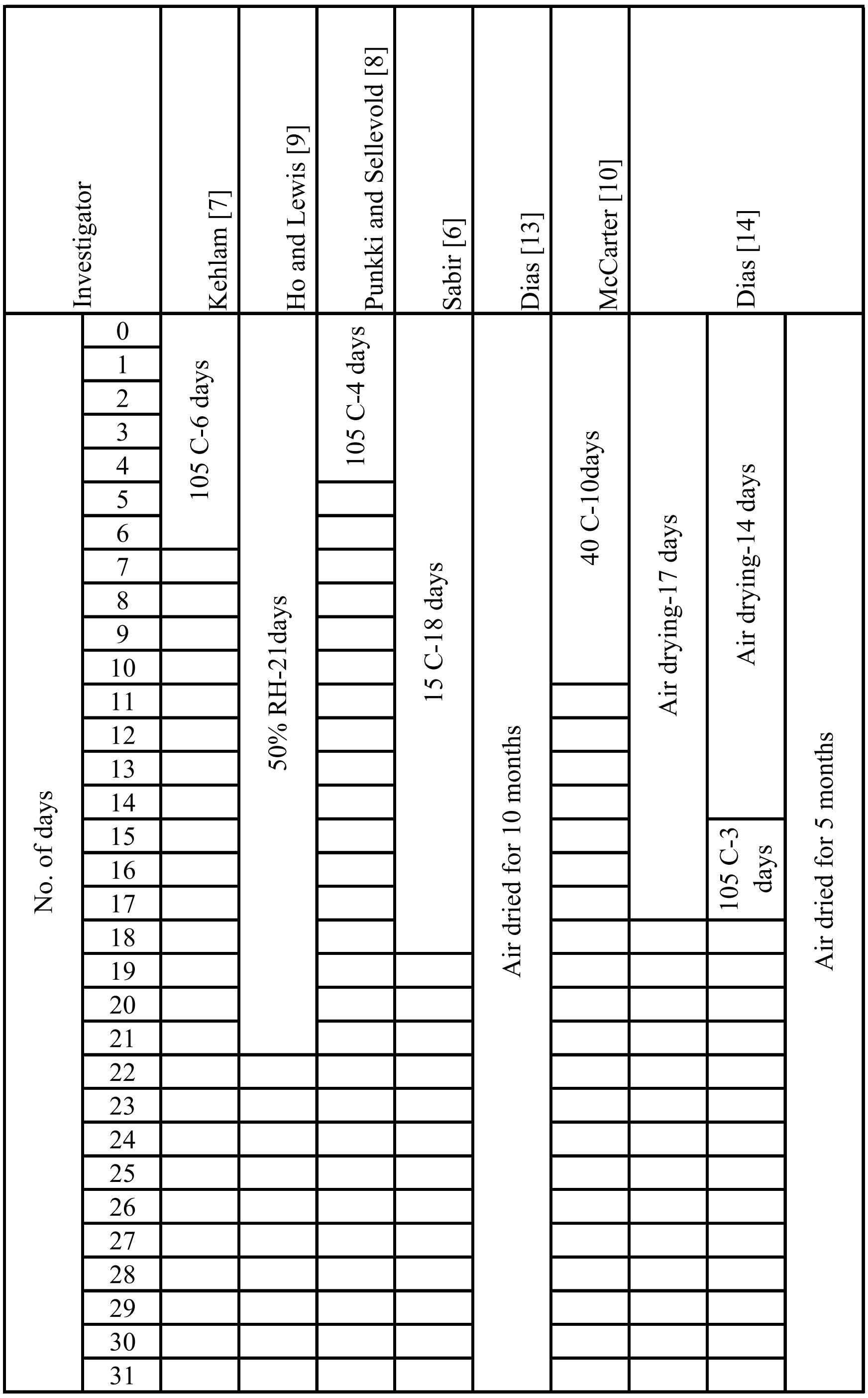

Figure 30 Various preconditioning methods used by different researchers

The sample coating and immersion strategies for sorptivity testing are outlined in Table 21.

Table 21 Coating and immersion strategy for sorptivity samples

Description	Face	Top (T)	Middle (M)	Bottom (B)
	Top	No	Yes	No
Coating	Circumference	Yes	No	Yes
	Bottom	No	Yes	No
	Top	in water	in air	covered
Immersion	Circumference	in air	in water	in air
	Bottom	covered	in water	in water

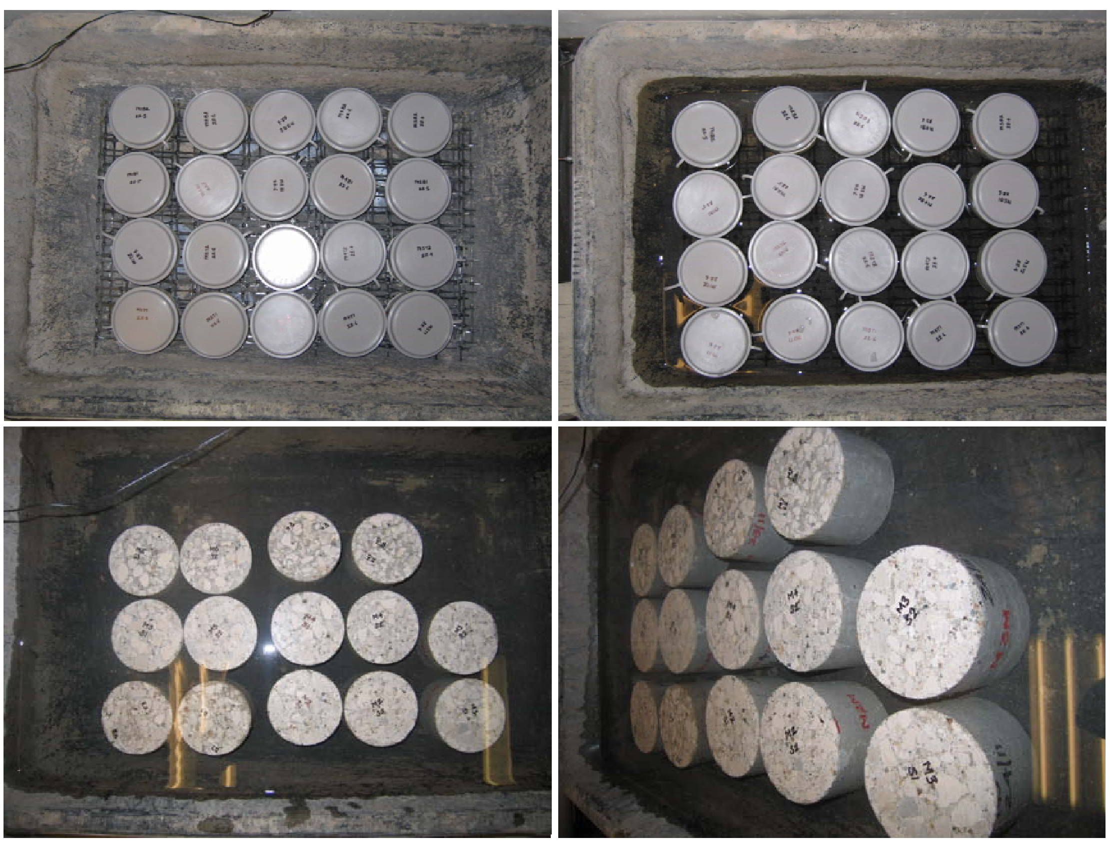

Figure 31 Sorptivity samples soaked in water

3.5.4 Permeable Voids and Water Absorption

Specimens similar to the sorptivity tests were prepared to access the variation in the permeable voids content and are shown in Figures 32 and 33. These tests were conducted at the age of 28 days.

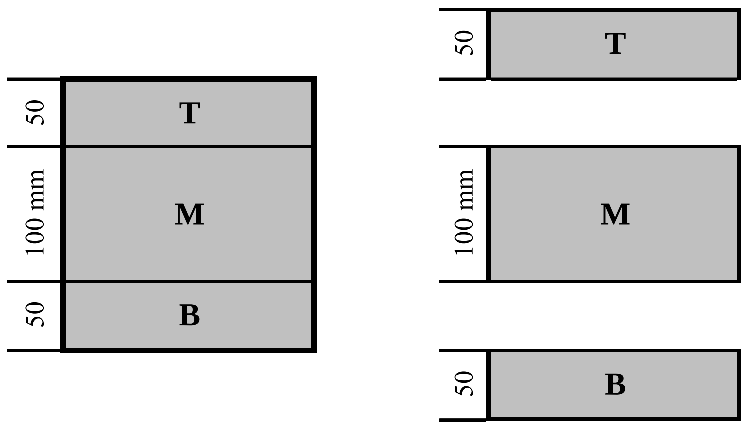

Figure 32 Original cylinder with markings and cut specimens for Voids content

3.5.5 F-T testing

For cyclic F-T testing of these mixes, cores of Φ 75 mm × 300 mm were extracted from the cast beams at the age of 21days (after curing for 21 days) and were saturated for 48 hours before beginning the tests. Figure 34 shows the schematic sketch of the core extraction scheme, while Figure 35 shows some of the actual pictures taken during the core extraction process.

Figure 33 Cutting of slices for voids content

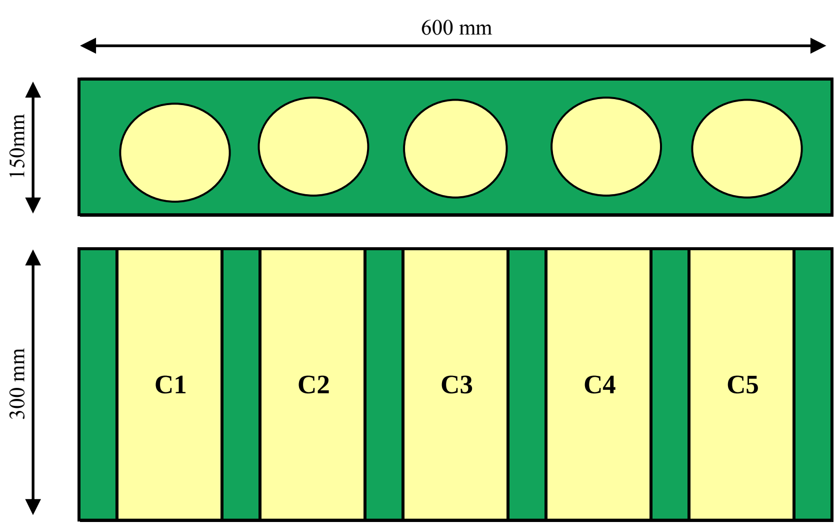

Figure 34 Schematic sketch of samples extracted for F-T testing

Figure 35 Core extraction

3.6 Mix Proportioning

Mixes were proportioned with different cement contents while keeping the consistency constant (40 ± 10 s). Soil analogy method was used in deciding the OMC-MDD.

Synopsis

The experimental plan is devised to cover a wide range of cement contents starting from 100 kg/m^3 to 450 kg/m^3, which would cover all possible pavement applications. Primary tests like consistency of the mixes, moisture-density profiles, and compressive strength shall be conducted to characterize the concrete. In addition to this, the water transport behavior in these mixes shall be understood with the help of water absorption, permeable voids content and sorptivity tests. A non-standard desorptivity test shall be performed to understand the drainage behavior of all the mixes. Subsequently accelerated F-T tests would be conducted to understand the responses of these mixes to the hydro-thermal loading. SEM imaging shall be carried out to understand the air void sizes and their spatial distribution.

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4 RESULTS AND DISCUSSIONS

Summary

This chapter presents a summary of all the test results of this investigation. Initially the fresh properties of the mixes in terms of Ve-be time and moisture-density profiles are described in detail. An elaborate discussion on the mechanical property-compressive strength follows this section. Discussions on the properties like voids content, water absorption, sorptivity and desorptivity follow along with the introduction to some of the new characterizing parameters. Subsequent to this results and discussions on F-T resistance and SEM analysis are reported. Elaborate discussions on these properties followed by relevant conclusions are included in the latter part of the chapter.

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4.1 Precision and bias statement

All the tests were performed strictly according to the relevant ASTM standards. The precision and bias statements were prepared, checked and verified in accordance with ASTM C670 and the individual test standards. The values of standard deviation, coefficient of variation and tolerance were checked against the specified values of single laboratory-single operator. All the values were found to be within the specified limits and a more detailed discussion of this is considered to be trivial in nature.

4.2 Results and discussion

4.2.1 Evolution of mix proportions

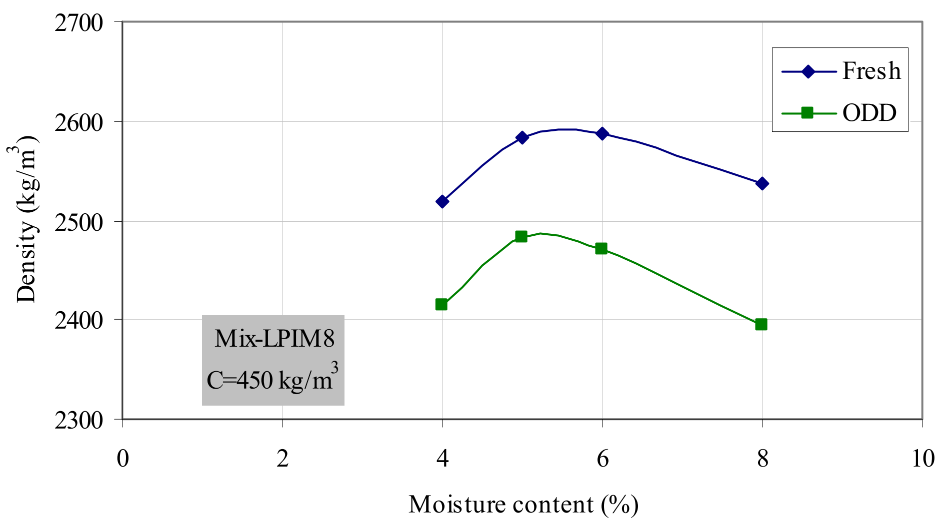

Figure 36 Typical moisture density profile

Moisture-density plots were evolved for each set of cement content, aggregate content and chemical admixture(s). Figure 36 shows two typical moisture-density plots. Utilizing these, the optimum moisture content (OMC) and maximum dry density (MDD) for each mix was evaluated. Table 22 provides the final mix proportions used for specimen casting for testing purposes along with the consistency measured using Ve-Be consistometer.

Table 22 Mix proportions for RCC mixes

Phase	Mix	Cement (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)	WR (kg/m^3)	AEA (kg/m^3)	Water (kg/m^3)	VBT (s)	NAMC (%)	MDD (kg/m^3)
LPI	LPIM1	100	1178	954	1.5	0	127	65	7.80	2385
	LPIM2	150	1103	982	2.3	0	128	50	7.84	2425
	LPIM3	200	1056	996	3.0	0	125	47	7.65	2450
	LPIM4	250	918	1087	3.8	0	125	43	7.71	2500
	LPIM5	300	854	1113	4.5	0	123	45	7.59	2520
	LPIM6	350	791	1137	5.3	0	122	39	7.52	2490
	LPIM7	400	730	1157	6.0	0	121	38	7.45	2470
	LPIM8	450	671	1176	6.8	0	120	40	7.37	2480
LPII	LPIIM2	150	1104	984	2.3	1.2	127	42	7.79	2410
	LPIIM4	250	924	1094	3.8	2	120	46	7.46	2536
	LPIIM6	350	795	1142	5.3	2.8	118	38	7.32	2518
	LPIIM8	450	676	1184	6.8	3.6	115	41	7.13	2430

Notes: FA: Fine aggregate; CA: Coarse aggregate; WR: Water reducer; AEA: Air entraining agent;
NAMC: Nominal actual omoisture content; MDD: Maximum dry density

4.2.2 Consistency

As was anticipated the water demand for leaner mixes was having higher water demand and had longer VBT, while richer mixes had relatively lesser water demand from aggregates and hence shorter VBT. VBT is highly subjective test and this has been substantiated in the literature [1]. From Table 22, it can be observed that with the increase in the cement content of the mixes, the NAMC showed a slight drop and similar trend was observed for the VBT. Similar observations regarding NAMC were made by previous researcher with fly ash mixes [2]. Leaner mixes didn't have sufficient paste to form a good ring and hence had much longer VBT, while richer mixes had sufficient paste and due to relatively richer consistency had shorter VBT. Previous researcher substantiates this fact in an indirect fashion [2].

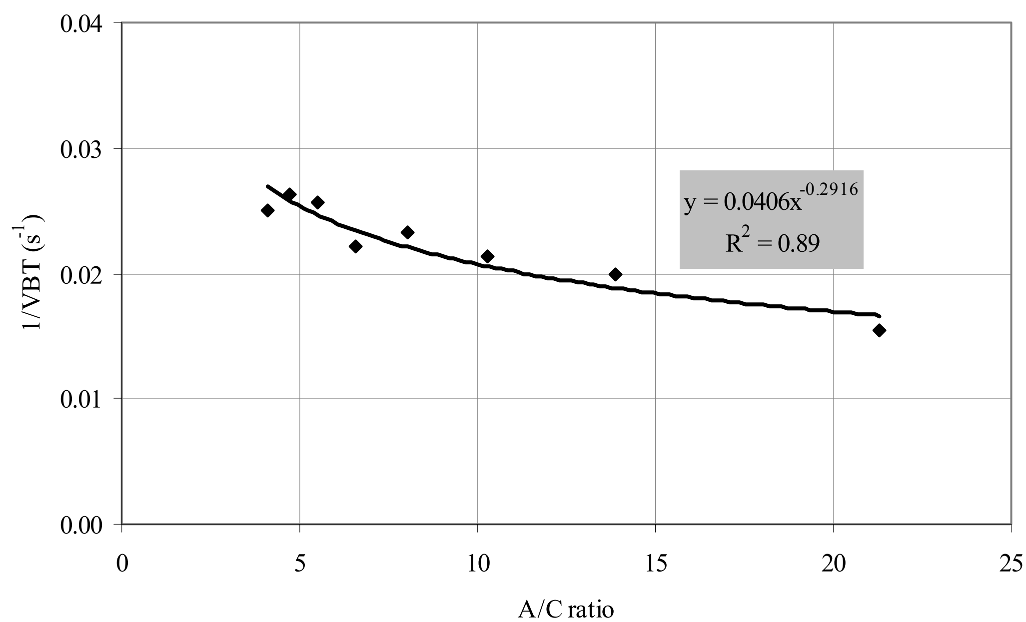

Figure 37 VBT and A/C ratio

Figure 37 shows a relationship of 1/VBT and A/C ratio. It was observed that the inverse of VBT was a better parameter for defining this relationship than the VBT itself. It can be observed from the graph that for a given consistency, as the A/C ratio increases, the VBT increases. This relationship is defined by a power function, since the regression of the available date shows that this relationship predicts the values of 1/VBT in a better fashion than the exponential relationship. Moreover this form of relationship predicts realistic values. Physically this means that with an increase in the A/C ratio (x-variable), which is in the denominator leads to a decrease in the inverse of VBT or increase of VBT implying that the mix becomes stiffer.

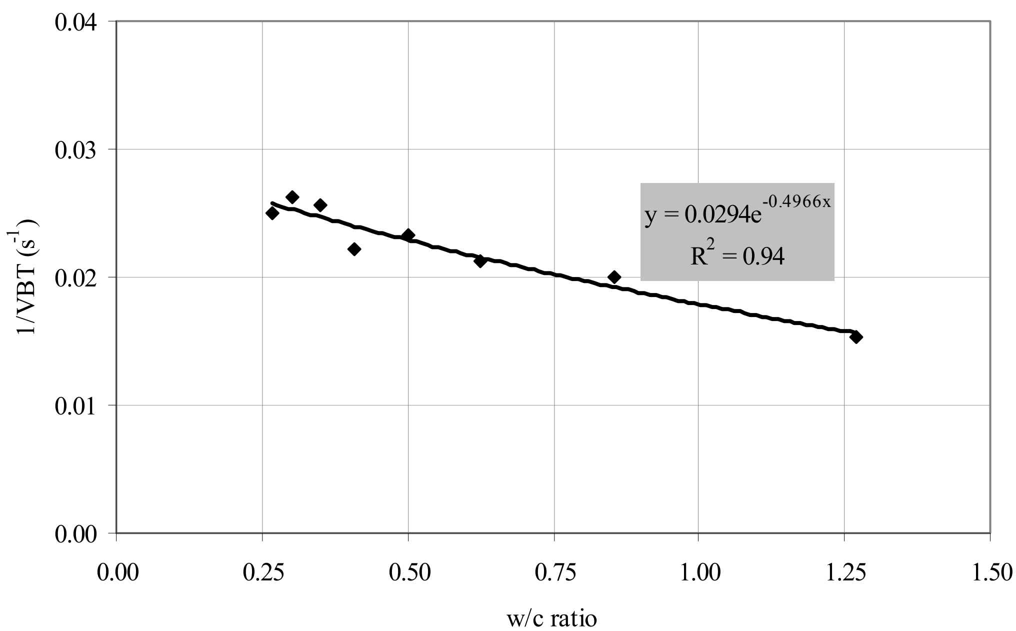

Figure 38 VBT and w/c ratio

Figure 38 shows the relationship between the inverse of VBT and the w/c ratio. It can be seen from the plot that as the cement content of the mix decreases the w/c ratio values approach unity and go well beyond unity. Moreover higher w/c ratios imply higher A/C ratio which means stiffer consistency or higher VBT. Arguing in the same fashion, it can be seen from the plot that as the w/c ration decreases (or cement content increases or A/C ratio decreases), the volume of paste in concrete increases with the voids content in aggregates remaining more or less constant. This also means that the aggregates are having more inter-particular spacing and this space is now covered with a thicker layer of paste, in contrast to the leaner mixes, where the aggregates may be in direct point-to-point contact. Thus for a given vibrational energy, the mixes with higher paste content will have faster rising of slurry from the mix in a fixed amount of time when compared to leaner mixes. Thus as the w/c ratio decreases the VBT decreases of the inverse of the VBT increases. Mathematically the exponential relationship defines the relationship and thus predicts the values of inverse of VBT with greater accuracy. Hence this form of equation was chosen. These relationships are unique, since in author’s knowledge this has been defined for the first time in such a manner.

4.2.3 OMC-MDD relationships

Figure 39 shows the relationship of MDD and cement content of the mixes. These curves were evolved with an objective of understanding the evolution of MDD with cement content. As can be see from the curves that adding air entraining agent does not make a significant different in the strength of concrete. Even though the general trend is clearly perceptible, but statistically these differences between the two series of mixes are insignificant. The curves show that the MDD increases gradually as the cement content increases, reaches a maximum value and then starts decreasing. The maximum percentage increment is about 5% for LPI mixes w.r.t. to the lean-most mix with a subsequent decrease of about 2%. Similar values for LPII mixes are 6% and 5% respectively. The effect of air entrainment is negligible or none at all.

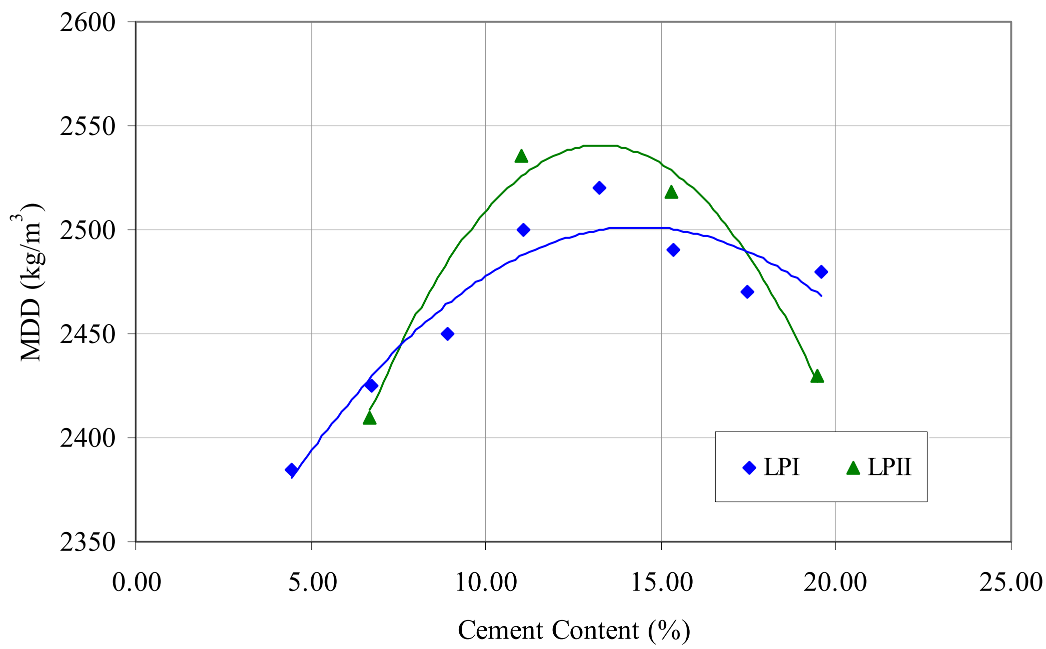

Figure 39 Variation of maximum dry density with cement content

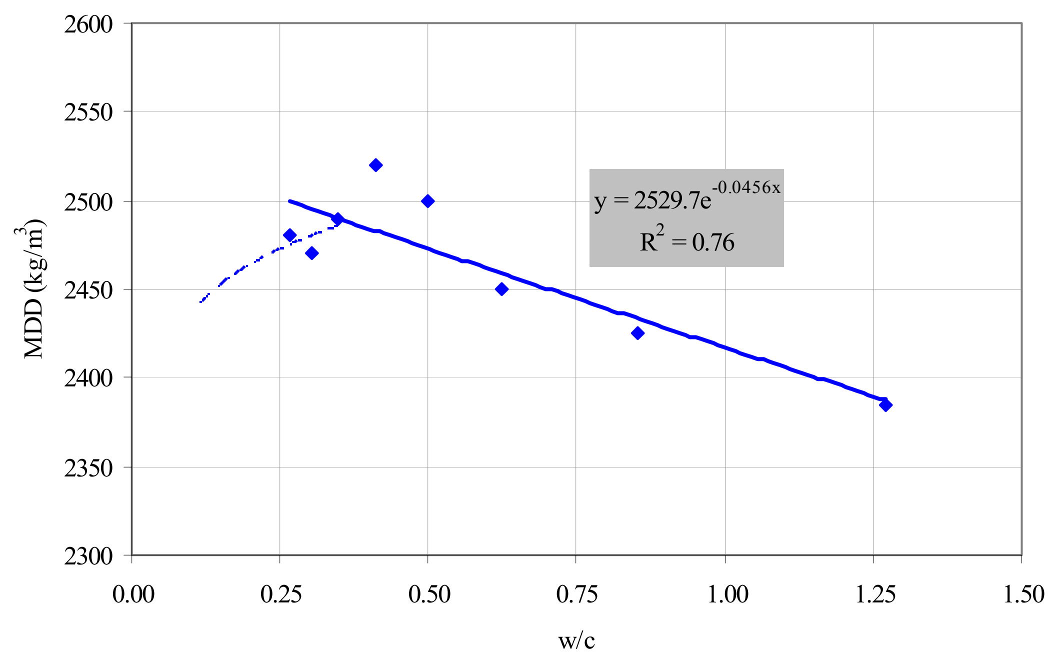

Figure 40 Variation of maximum dry density with w/c

Figure 40 shows the trend of dry density with the w/c ratio of the mixes for PI. Similar curve can be plotted for PII mixes. Conventionally this curve is plotted against water content [3] to understand the variation of fresh density with the increase in water content and is a straight line. In case of the current series of mixes, the curve is however showing an exponential decrease in dry density with increase in w/c ratio. This may also be interpreted as straight line. This is another way of appreciating the decrease in density w.r.t. w/c of the mixes. This curve is more fundamental in nature than the curve shown in Figure 39, since it correlates a more fundamental parameter of concrete, w/c to the MDD of concrete.

The general trends can be explained on the basis of the particle size distribution and nature of the paste in these mixes. Mixes with relatively lower cement contents would have a higher A/C ratio and just sufficient water resulting into higher shearing action than the viscous action in paste. This also makes the compaction of particles difficult due to lesser mobility or higher resistance to movement. This in turn combined with the usage of more materials with relatively lesser specific gravities (aggregates as compared to cement) leads to lowering of density and increase in the voids content of the mixes when compared to the richer mixes. This also leads to the formation of relatively more pervious surface texture of concrete and poor finishibility.

As the compaction of the particles becomes denser along with the inclusion of finer material in the form of cement a stage is reached when the particles are packed to the maximum practical packing possible. Consequentially, a flat region develops on the curve as the cement content and cement-water-aggregate system reaches its maximum value of density for the defined compaction energy. Subsequent to this, the mobility of the cement-water-aggregate system is so arranged that it leads to a decrease in the density of concrete. In this region the compaction processes are governed by the viscous nature of cement paste more than the shearing nature of the cement paste, since the cohesion of the mixes is much more than the lower cement content mixes.

One of the important yet underestimated parameters in RCC is PSD of the combined aggregate grading and its response to method of compaction. In the current research the compaction method used was the vibrating impact hammer. This hammer provides a heavier and stronger loading, which when combined with the relatively stronger confinement to the plastic molds by the steel sleeve makes the concrete independent to move only in one direction. Conjugated with this fact are the strength of aggregates and their response to impact loading plays a crucial role in maintaining or changing the aggregate grading and the response of the resulting aggregate skeleton to mechanical and hydraulic loading. The fact that the limestone used in this research is having a relatively higher abrasion value (about 40%) adequately supports the fact that these aggregates are going to respond poorly to the impact loading. This also means that this type of loading might also fracture internally and/or thoroughly under such kind of loading eventually leading to poor F-T performance of concrete.

4.2.4 Compressive strength

Unconfined cylinder compressive strength (UCS) was measured at 7 and 28 days. Table 23 provides a summary of UCS for both the series. The efficiency factor as defined in chapter 2 is also shown in the final column. This helps in analyzing the unit strength contribution to the strength by unit quantity of cement for a fixed quantity of concrete. Figure 41 shows the typical nature of fractures in these mixes.

Table 23 Compressive strength and efficiency factor

Phase	Mix	Cement (kg/m^3)	UCS, MPa 7d	UCS, MPa 28d	UCS, MPa 7/28	η ($kgf.m^3/kg.cm^2$)
LPI	LPIM1	100	6.22	14.78	0.421	0.50
	LPIM2	150	15.60	25.46	0.613	1.24
	LPIM3	200	28.65	40.05	0.715	2.34
	LPIM4	250	46.44	51.88	0.895	3.79
	LPIM5	300	40.12	55.76	0.720	3.33
	LPIM6	350	49.46	57.74	0.857	4.14
	LPIM7	400	46.92	57.76	0.812	3.96
	LPIM8	450	43.48	55.46	0.784	3.70
LPII	LPIIM2	150	18.60	25.50	0.729	1.49
	LPIIM4	250	42.20	45.32	0.931	3.59
	LPIIM6	350	46.20	51.64	0.895	3.99
	LPIIM8	450	40.50	50.90	0.796	3.59

Figure 41 Cracking pattern in compressive strength test cylinders

Figure 42 shows the relationship of cement content (%) and UCS. It can be seen that the strength of the mixes increases as the cement content increase, obtains a maximum value and then starts decreasing. Thus there exists optimum cement content for constant consistency and given aggregate gradation. Similar trends is observed in both the series of mixes, except for the fact that the LPII mixes which have air entrainment showed a slight reduction in strength except for M2 mixes. This relationship is very well defined in RCC mixes when compared with CVC cited in the literature [4]. This relationship also shows that there is no incremental advantage obtained in terms of strength gain by adding more cement to the RCC mix after the optimum value. Infact additional cement might lead to increased admixture demand making the mixture more expensive.

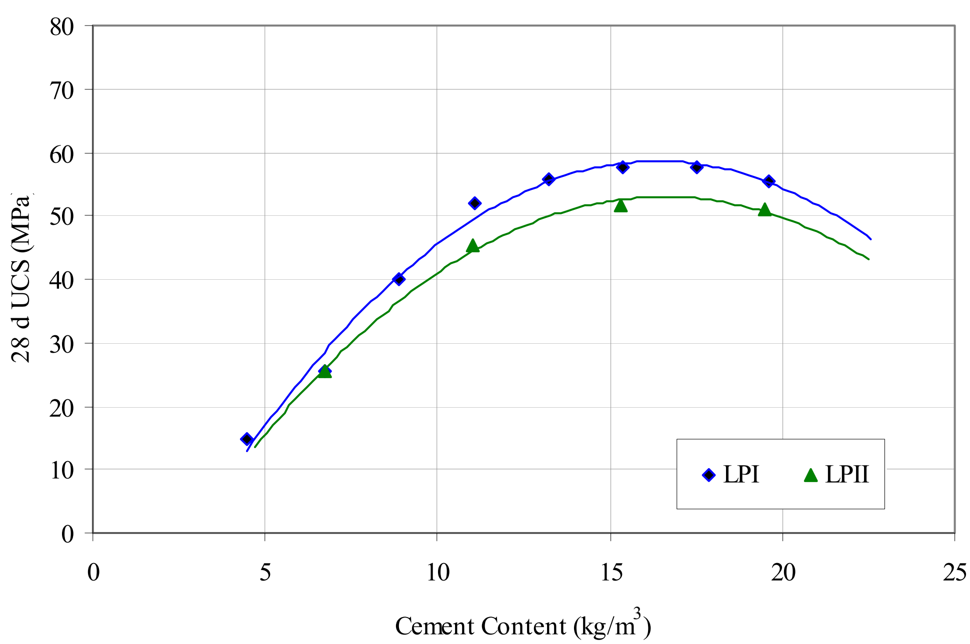

Figure 42 Variation of compressive strength with cement content

A way of appreciating the strength evolution of a series of mixes is to plot the 28 days strength against w/c. Figure 43 represents such an evolution. It can be seen from the curve that unto mix M6 the w/c-strength ratio law applicable to conventional concrete is followed. Beyond M6 there is reduction in strength as the w/c ratio decreases. In this study all the mixes were compacted for a fixed amount of time (40 ± 5 sec per layer) for comparison purposes. Beyond a certain point on working curve, if the concrete is dry and vibrated, then it shows a drop in strength. This can be explained on the basis of the stresses induced by shrinkage, whose restraint by aggregates particles causes cracking of the cement paste or a loss of aggregate-paste bond. This happens especially at lower w/c and higher cement contents [3].

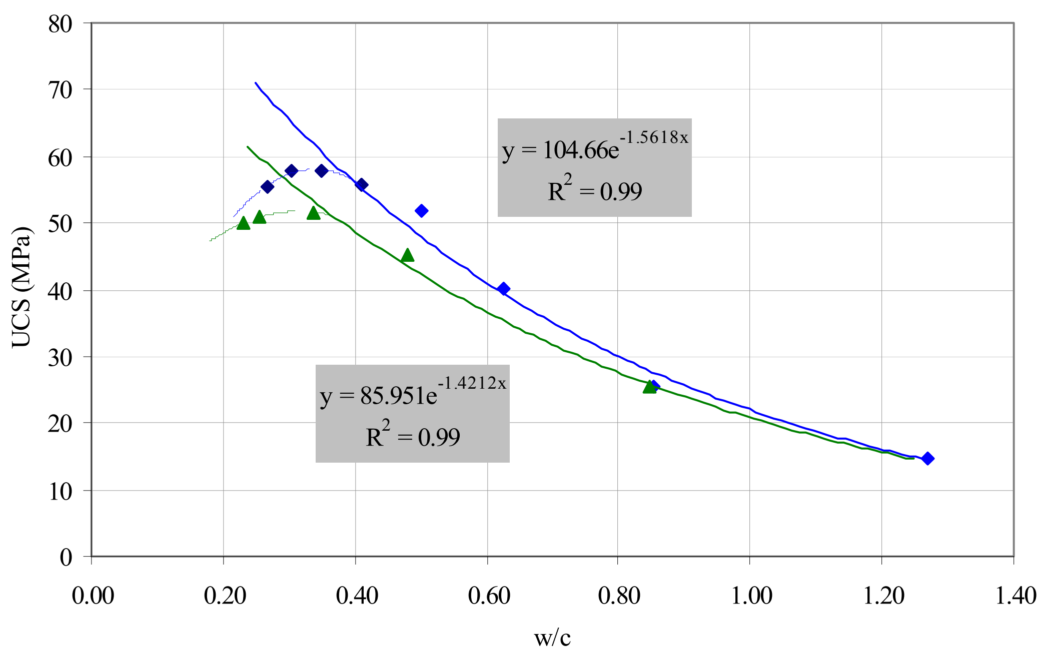

Figure 43 Variation of compressive strength with w/c

It can also be observed that air can be entrained in RCC mixes and is adequately reflected in the strength curves. It is difficult to entrain air in leaner mixes than richer mixes due to lower paste content and relatively drier consistency. In addition to this there were notable differences in the nature of fracture at the failure with lower cement content mixes showing failures at the ITZ to sharp cone failures passing through the aggregates in richer mixes.

Figure 44 shows the relationship between the UCS and MDD for different mixes from series LPI. It can be seen from the relationship that strength increases with increase in the density of the mixes. This is no universal relationship and this study very well acknowledges its limitations.

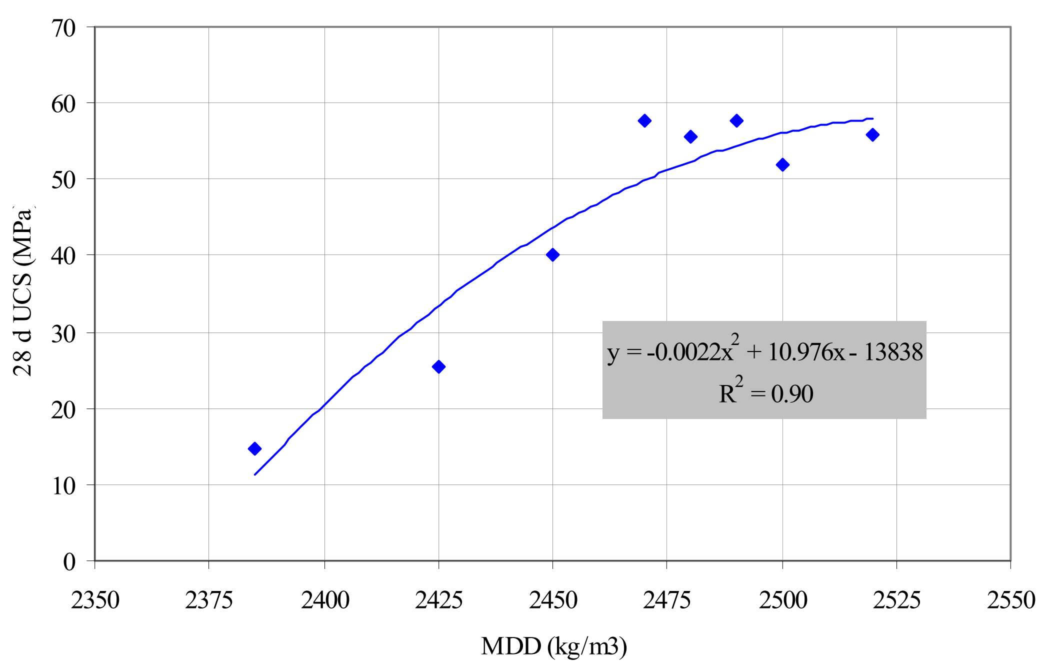

Figure 44 Variation of compressive strength with maximum dry density

Figure 45 shows the efficiency of the mixes as a function of w/c ratio. In this representation of nature of strength evolution it can be seen that unit contribution of the strength of concrete by unit quantity of cement decreases as the w/c ratio increases. Air entrainment in concrete mixes certainly reduces the contribution of cement in the strength evolution of concrete, thus justifying the efficiency factor reduction with increase in the w/c ratio. In addition to this the efficiency factor can be similarly related to the A/C ratio of the mixes.

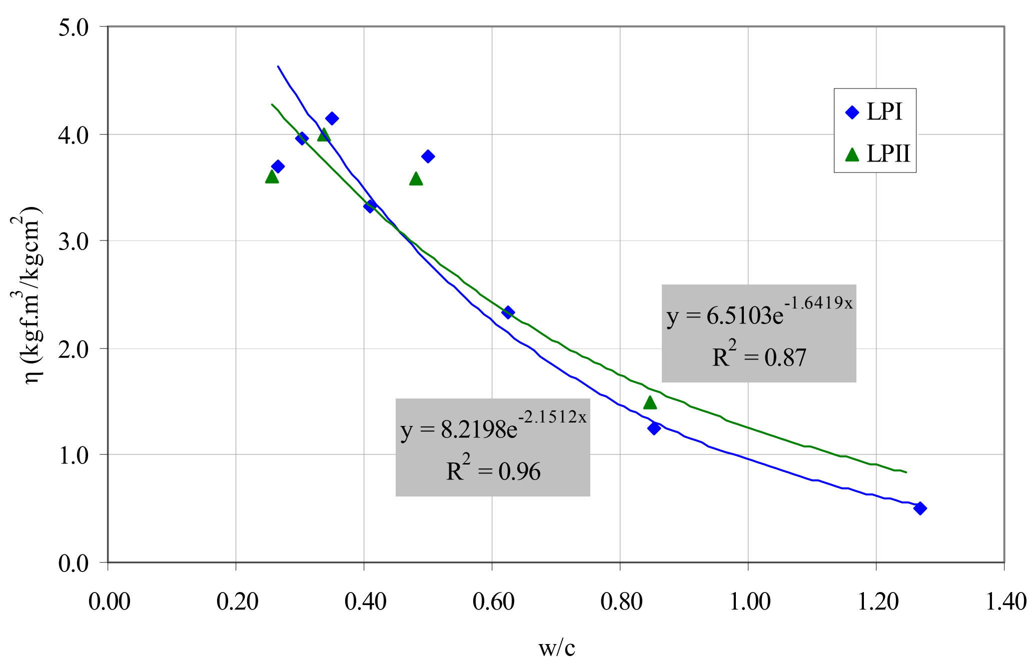

Figure 45 Variation of efficiency factor with w/c

It can be seen from the data that the strength decreases as the cement content increases. The strength curves drawn versus w/c ration show a drop below a certain w/c ratio.

This is a consequence of the incomplete compaction which is also reflected in lowering of compacted dry density. Air entrainment produces its effects on the strength changes with a more pronounced effect at relatively higher cement content. This can be understood from the dry nature of the concrete at lower cement contents with relatively higher A/C ratio.

4.2.5 Water absorption

Table 24 shows the water absorption, density and permeable voids content of different portions of concrete. The 24 hr water absorption varied from 3.36 to 5.53 % for LPI mixes while it varied from 3.4 to 5.32 % for LPII mixes. Available data suggests no definite conclusion for the effect of entrained air in concrete.

Figure 46 shows the typical water absorption for different portions of comparative mixes from the two series. Irrespective of the mix type, the bottom portions of the cylindrical samples consistently showed a lesser water absorption value than the corresponding top portions. The middle samples showed the least amount of water absorption. Similar trends were observed for all the mixes in both the series.

Table 24 Water absorption and permeable voids content

Phase	Mix	Sample	A_i (%)	A_{ib} (%)	γ_d (kg/m^3)	γ_i (kg/m^3)	γ_{ib} (kg/m^3)	γ_{app} (kg/m^3)	n_p (%)
LPI	LPIM1	Top	5.29	5.66	2,261	2,381	2,389	2,593	12.8
		Middle	4.81	5.16	2,292	2,403	2,411	2,600	11.8
		Bottom	5.00	5.58	2,273	2,386	2,400	2,603	12.7
	LPIM2	Top	4.61	5.08	2,292	2,398	2,409	2,595	11.6
		Middle	4.10	4.45	2,322	2,418	2,426	2,590	10.3
		Bottom	4.24	4.58	2,307	2,404	2,412	2,579	10.6
	LPIM3	Top	4.31	4.92	2,299	2,398	2,412	2,592	11.3
		Middle	3.72	4.06	2,324	2,410	2,418	2,566	9.4
		Bottom	4.14	4.61	2,319	2,415	2,426	2,597	10.7
	LPIM4	Top	4.07	4.65	2,309	2,403	2,417	2,587	10.7
		Middle	3.36	3.76	2,335	2,413	2,423	2,559	8.8
		Bottom	4.41	4.81	2,328	2,431	2,440	2,622	11.2
	LPIM5	Top	4.17	4.48	2,316	2,412	2,420	2,584	10.4
		Middle	3.54	3.89	2,340	2,423	2,432	2,575	9.1
		Bottom	3.78	4.17	2,335	2,423	2,432	2,587	9.7
	LPIM6	Top	4.40	4.73	2,305	2,407	2,414	2,587	10.9
		Middle	3.99	4.28	2,331	2,424	2,431	2,589	10.0
		Bottom	3.78	4.19	2,327	2,415	2,424	2,578	9.8
	LPIM7	Top	5.00	5.33	2,286	2,401	2,408	2,603	12.2
		Middle	3.98	4.30	2,328	2,421	2,428	2,587	10.0
		Bottom	3.98	4.50	2,309	2,400	2,412	2,576	10.4
	LPIM8	Top	5.53	5.94	2,276	2,401	2,411	2,631	13.5
		Middle	4.84	5.17	2,295	2,406	2,414	2,605	11.9
		Bottom	4.35	4.79	2,318	2,419	2,429	2,608	11.1
						,	,	,	
LPII	LPIM2	Top	4.44	4.91	2,275	2,376	2,386	2,561	11.2
		Middle	4.16	4.50	2,267	2,361	2,369	2,524	10.2
		Bottom	4.43	4.76	2,251	2,350	2,358	2,520	10.7
	LPIM4	Top	4.00	4.48	2,317	2,409	2,421	2,585	10.4
		Middle	3.40	3.80	2355	2,435	2,444	2,586	8.9
		Bottom	3.69	4.11	2,327	2,413	2,423	2,574	9.6
	LPIM6	Top	4.31	4.60	2,341	2,442	2,449	2,623	10.8
		Middle	4.14	4.45	2,341	2,438	2,445	2,613	10.4
		Bottom	4.26	4.70	2,339	2,439	2,449	2,628	11.0
	LPIM8	Top	5.32	5.71	2,276	2,397	2,406	2,616	13.0
		Middle	5.22	5.55	2,280	2,399	2,406	2,609	12.6
		Bottom	5.08	5.48	2,285	2,401	2,411	2,613	12.5

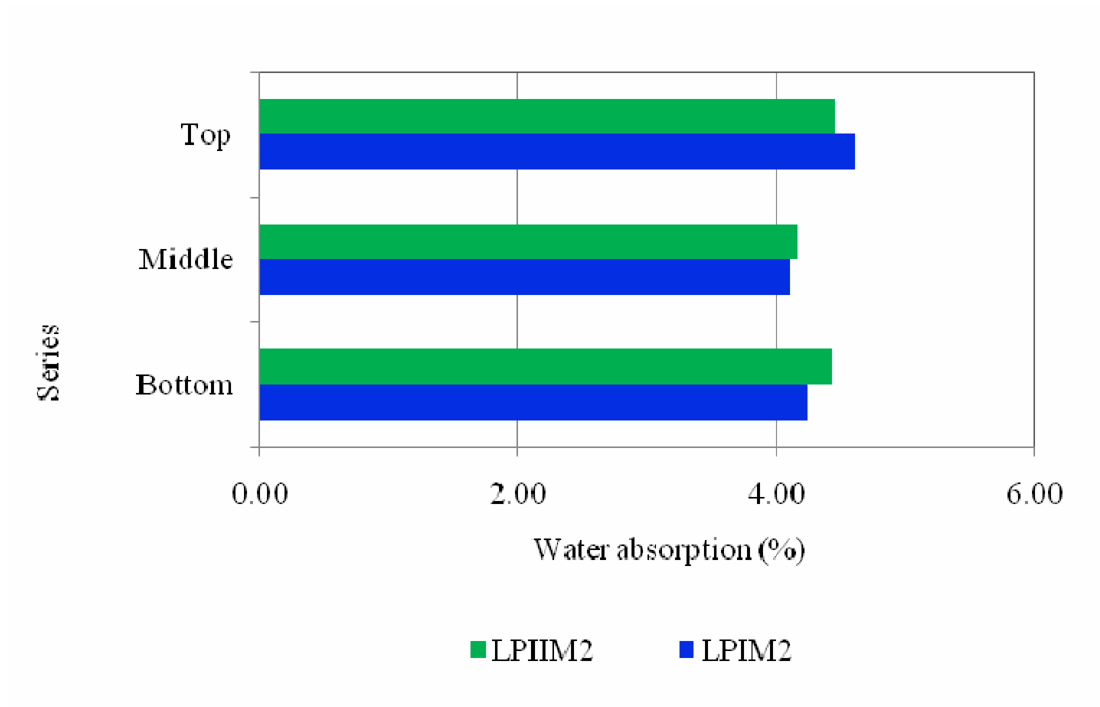

Figure 46 Variation of water absorption with depth

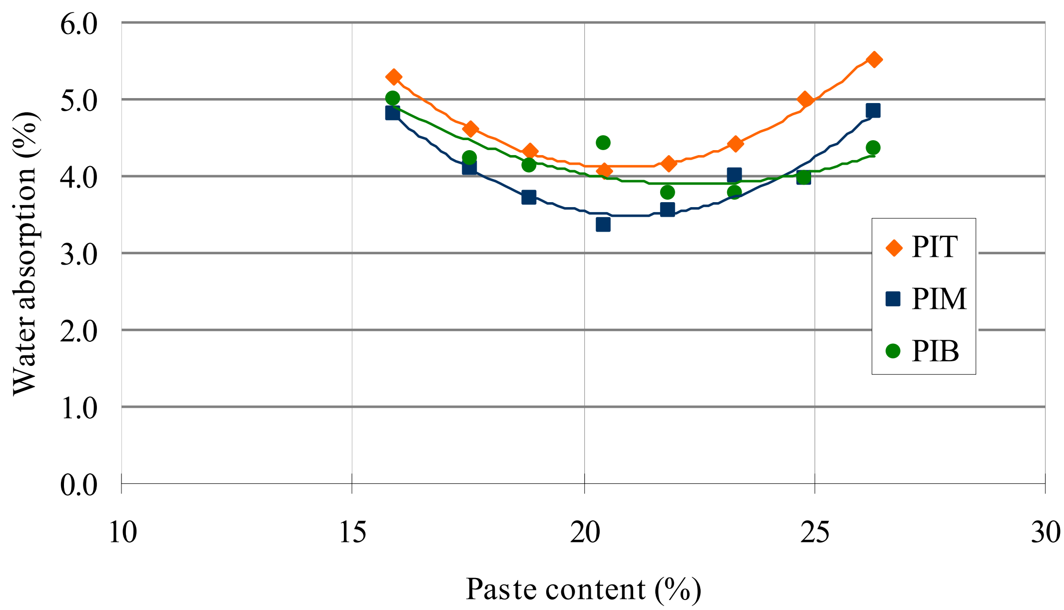

Figure 47 Variation of water absorption with cement content and depth

Figure 47 shows the variation of water absorption values with the paste content (by weight) of the mixes from series LPI. A similar curve can be constructed with cement content on x-axis, but with w/c ratio on x-axis, a general trend is difficult to obtain. This is shown in Figure 48. It can be seen that the water absorption values are higher for the lower cement content mixes, gradually decreased as the paste content increased to reach minimum values in the range from 20-23 % of paste content and then again showed an increasing trend. Irrespective of the mix series, a similar trend was observed. The literature lacks such a comprehensive set of data on these variables.

Figure 49 shows the comparison of all the corresponding mixes from both the series. Apart from the general trend described in earlier paragraphs, no statistically significant differences were observed in the water absorption values of the mixes, i.e. effect of air entrainment is not perceptible in these mixes.

The water absorption values of the mixes incorporating lower cement contents is lower and can be explained on the basis of the lower cement and hence paste content. The drier nature of these mixes further enhances the water absorption values. As the cement and hence the paste content of the mixes increases a minimum value is reached at which the cement paste is at its optimum maximum density leading to a better barrier performance to the penetration of the fluids-in this case water. As the cement content increases the water absorption values again shows an increasing trend. This matter needs further investigation beyond and is beyond the scope of this thesis.

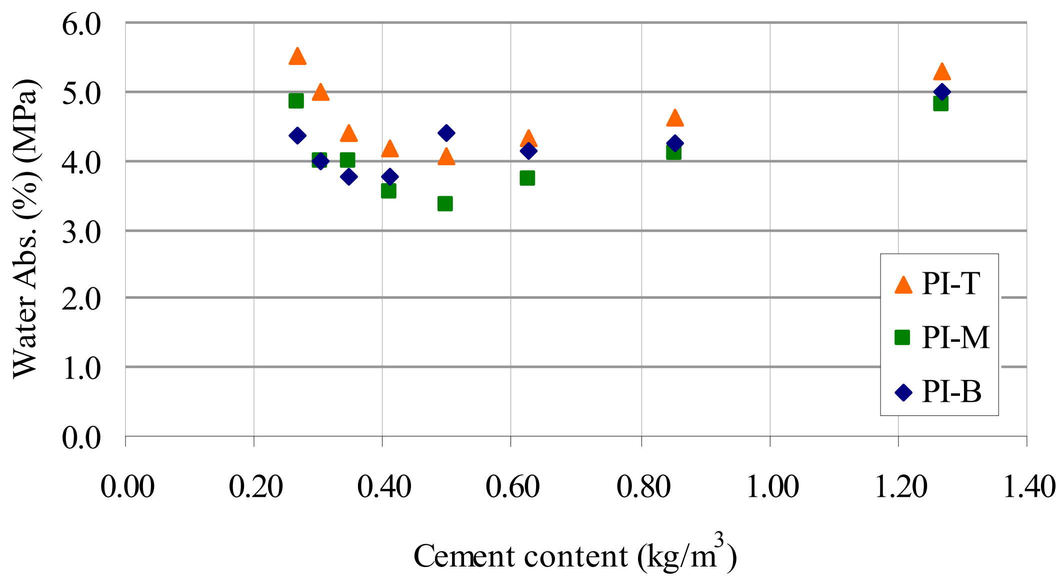

Figure 48 Variation of water absorption with w/c and depth

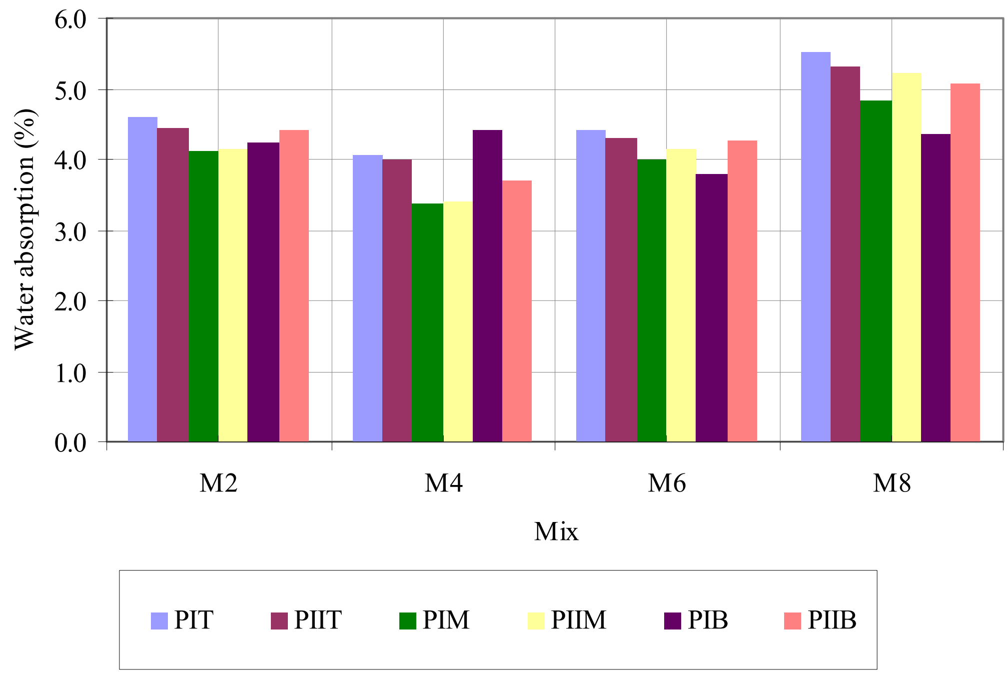

Figure 49 Effects of air entrainment on water absorption of concrete

Variation of concrete water absorption with depth can easily be understood by the process of compaction. The bottom (B) layer gets the maximum compaction and has one internal or unexposed face, an exposed face and an exposed circumference. The middle sample has two internal sides/faces and an exposed cylindrical surface. The top (T) part has one exposed face, one internal side and exposed circumference. The top part receives least amount of compaction and during compaction the rising sand particles (without cement paste at times) give a relatively higher porosity to the top concrete when compared to the other two specimen type. On the other hand the M specimens are confined on two faces where the reaction of cement with water is going on and these surfaces provide a lesser permeable barrier to the water transport when compared to the other two specimens. Due to the amount of compaction energies, the amount of exposed and unexposed surfaces and the corresponding water transport mechanisms, water absorption values of different portions of the mixes is different. These facts can be used for further understanding the water transport in pavements from bottom, top and sides.

Absorption in general cannot be used as a measure of quality control of concrete, but most good concretes have absorption well below 10 % by mass [5]. It is generally believed that the water absorption of conventional good quality concretes should be in 4-5% range. All the concretes tested in this study showed water absorption values above 4% with a few mixes showing values greater than 5%. This does not necessarily imply that the concrete is good or bad. ASTM C 936 [ASTM C 936 - Standard Specification for Solid Concrete Interlocking Paving Units] specifies a minimum compressive strength of 55.17 MPa (8000 psi) and a maximum water absorption value of 5% for the pavers to be F-T resistant. Research has indicated that block pavers with an average compressive strength of 55.17 MPa can be expected to endure between 250 and 275 cycles of freezing and thawing when subjected to the exposure conditions of rapid freezing and thawing test [5]. Another research [6] on RCC mixes incorporating Type V cement and class F fly ash indicated water absorption values of mixes in the range of 1.8 to 3.65 % but did not mention any correlation with other properties of concrete. In yet another research conducted on the masonry paver blocks, it was concluded that the water absorption value cannot be used as a predictor of Freeze-Thaw resistance of concrete. This matter will be further discussed in the section on NCMA frost index.

4.2.6 Permeable voids content

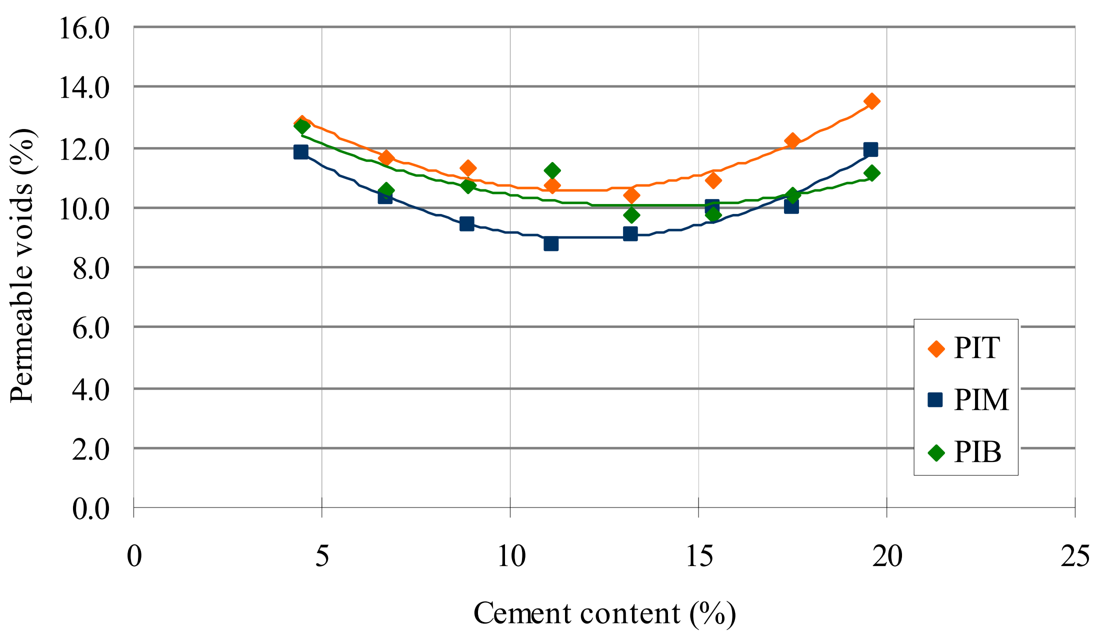

Figure 50 Variation of permeable voids content with cement content and depth

Figure 50 shows the general trend of series LPI mixes for permeable voids content. This trend is similar to what is observed for the water absorption for these mixes. In addition to this Figure 51 shows the variation of the permeable voids content for comparable mixes from both the series are shown

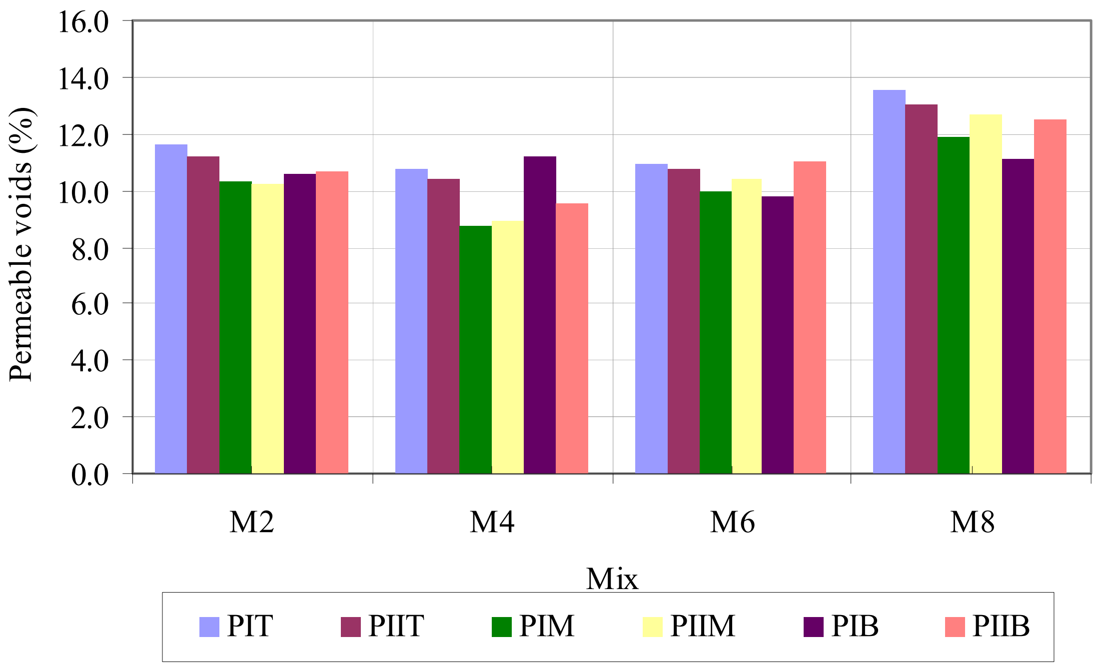

Figure 51 Effects of air entrainment on permeable voids content

It can be observed from Figure 50 the permeable voids content for the T samples was maximum and the M samples was minimum amongst the considered samples irrespective of the mix type. The B samples showed lesser permeable voids content than the T samples but had more voids than the M samples. This remained true for lower cement mixes, but changed for the higher cement mixes. With higher cement contents, the B samples showed the least permeable voids content with a clear trend of increasing voids content with height.

A general trend of the mixes shows an optimizing behavior similar to water absorption. The method utilized in characterizing the permeable voids content might not be foolproof, in terms of exerting sufficient force to penetrate all the permeable voids. The percentages of these voids are quite variable for these mixes. Further investigations into the appropriateness of this method would be useful.

4.2.7 NCMA Frost index

National concrete masonry manufacturers association (NCMA) has proposed an index [7] to predict the frost resistance of segmental retaining wall concrete units based on the fundamental parameters of compressive strength, 24 hr water absorption, and unit weight of the units. These parameters are obtained using the procedures outlined in ASTM C 140. NCMA has combined these parameters to evolve the following equation

$$I = \frac{(\text{unit density, pcf})*(\text{compressive strength, psi})^{1/2}}{(\text{absorption, pcf})}$$

This index has been used by researchers and was rated amongst the top parameters for characterizing the F-T resistance of concrete masonry units. [8]. Table 25 shows the frost index values calculated using the above formula.

Figure 52 shows the variation of the NCMA frost index with cement content. It can be seen that the nature of the curve again tends to optimize at particular cement content and decreases later on. NCMA prescribes to a minimum value of 2500 psi$^{0.5}$ for the masonry blocks to have maximum potency for Freeze-Thaw resistance. From the figure it can be seen that the LPII series, which in-effect is air entrained concrete and is found to be more F-T resistant compared to LPI non air entrained concrete mixes is predicted to be having lesser frost resistance.

Table 25 NCMA frost index for RCC mixes

Phase	Mix	Unit density (pcf)	Absorption (%)	Absorption (pcf)	UCS (psi)	I $(psi)^{0.5}$
LPI	LPIM1	149.20	5.03	7.51	2143	920
	LPIM2	150.25	4.32	6.49	3693	1408
	LPIM3	150.31	4.06	6.10	5808	1878
	LPIM4	150.81	3.95	5.95	7525	2197
	LPIM5	151.05	3.83	5.78	8087	2349
	LPIM6	150.77	4.06	6.12	8374	2255
	LPIM7	150.28	4.32	6.49	8378	2118
	LPIM8	150.38	4.91	7.38	8044	1828
LPII	LPIIM2	148.02	4.34	6.43	3698	1400
	LPIIM4	151.66	3.70	5.61	6573	2193
	LPIIM6	152.79	4.24	6.47	7490	2043
	LPIIM8	150.30	5.20	7.82	7382	1651

The natures of the curves shown in Figure 52 indicate that the frost resistance of the non-air entrained concrete is comparatively more than the corresponding air entrained concrete mixes. In addition to this the actual rapid F-T testing indicates that the air entrained concrete is more resistant to F-T loading. Furthermore this index has not been calibrated for RCC, which to a great extent limits its full application. The nature of the formula utilized is such that it depends on those macroscopic properties of concrete which may not be potent of characterizing the *micro-physical* phenomenon of frost resistance of concrete. There is certainly a big difference in the way a concrete responds to compressive loading, internal tensile loading and F-T loading, further investigation of this or another suitable indices would enhance our ability to predict the frost resistance of RCC mixes.

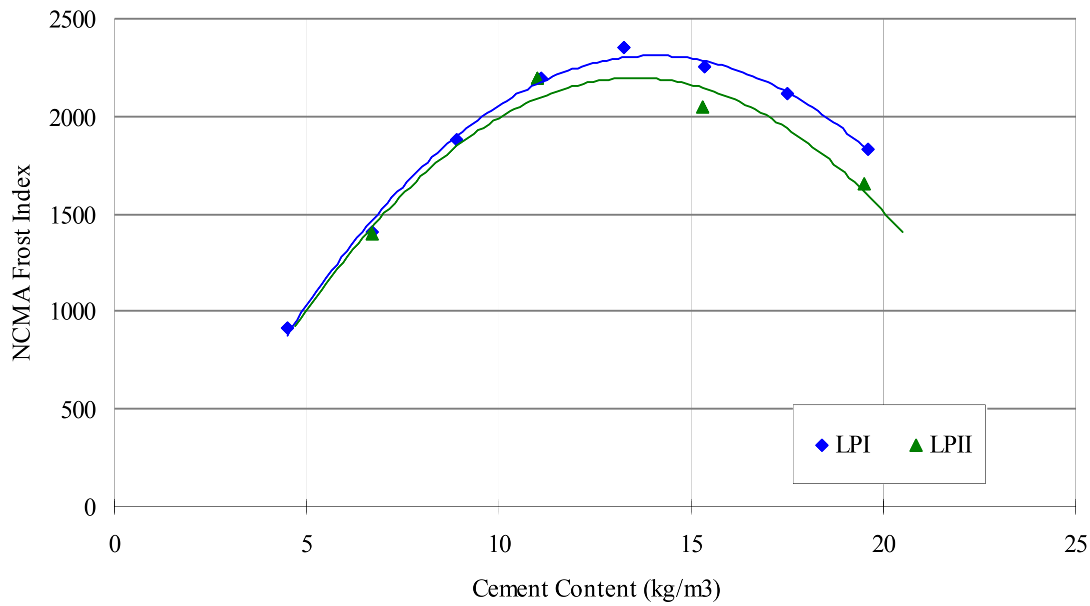

Figure 52 Variation of NCMA frost index

4.2.8 Desorptivity

Figure 53 represents typical desorption and dryness ratios for LPI mix at the start of the sorptivity tests. Desorption ratios can be used complementary to the initial moisture contents used for defining sorptivity function [9]. It can be seen that as the cement content increases the difference between the desorption ratios (Sat-Pre) and (Sat-OD) increases showing that drying at room temperature is not as effective for richer mixes as it is for leaner mixes. This also represents the fact that the richer mixes take longer time for loosing moisture than leaner mixes. Dryness ratio (DR) represents the relative amount of drying obtained by a certain preconditioning strategy w.r.t. standardized drying in relatively more controlled conditions. In this study the leaner mixes had DR values close to unity thus showing that the preconditioning method used in this study produced drying equivalent to the reference drying method. On the other hand the DR values increase with cement content showing that the preconditioning method is not as effective as the reference method of drying. Studies related to the effect of such drying and standardizing the reference drying procedures seems to be the next step in standardization. The author is therefore of the opinion without defining such dryness ratio the sorptivity values cannot be fully explained. There is thus a need for incorporating this strategy in the test standards to unify the diversity in measurement of sorptivity.

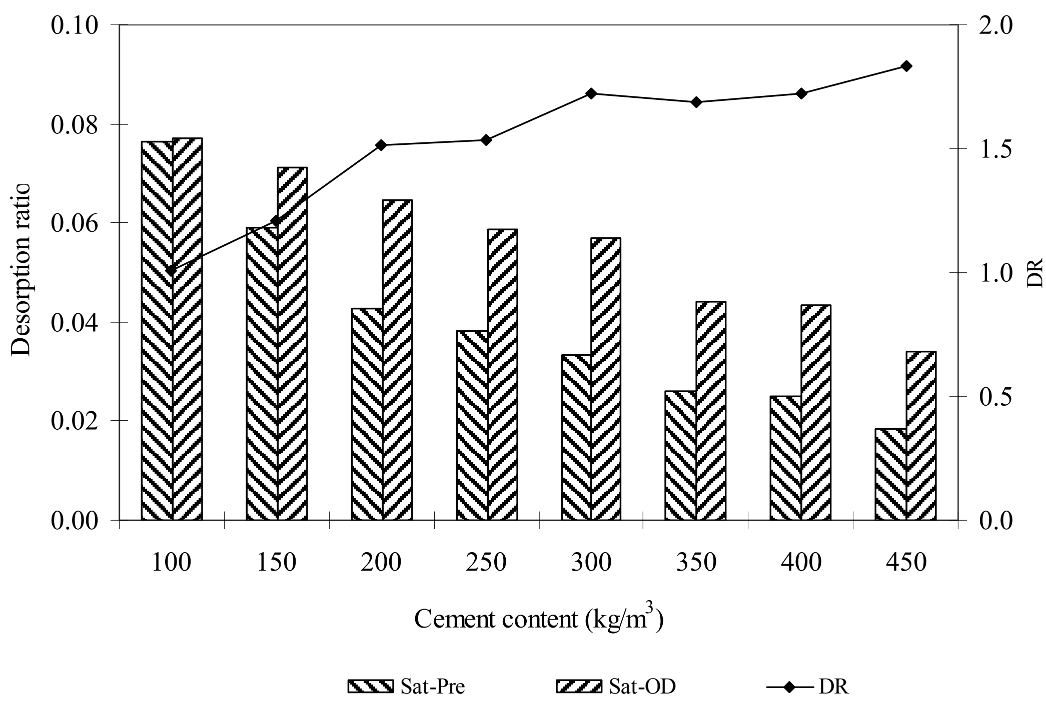

Figure 53 Desorption ratio, Dryness ratio and cement content

4.2.9 Sorptivity

Sorptivity measurements were done on the samples prepared in accordance with the scheme discussed in the Chapter 3. Figure 54 shows the typical trends observed during the sorption tests. These curves were then divided into two parts viz. initial six hours which defined the initial sorption profile of the mixes, and beyond 24 hrs which defined the secondary sorption profiles of the mixes. These differentiated trends are shown in Figures 55 and 56. The rate of water uptake and hence the sorptivity decreases with the increase in the cement content or decrease in the w/c. This is primarily decided by the dryness and porosity of the mixture. Leaner mixes tend to have more water uptake due to their porous nature. Leaner mixes could be imagined to be equivalent to masonry concrete units and thus having more capillary porosity for relatively more water uptake. The time period for the linearity between the water uptake and square root of time also depends on the mix. Leaner mixes showed longer time periods to reach linearity starting at about 70 hr; while richer mixes showed shorter time to reach linearity and showed steadier behavior. Moreover, leaner mixes tend to absorb more water initially due to drying of more large and interconnected pore structure. Faster water uptake in a concrete material represents poor barrier quality to water transport inside the concrete and in turn greater threat from the durability perspective.

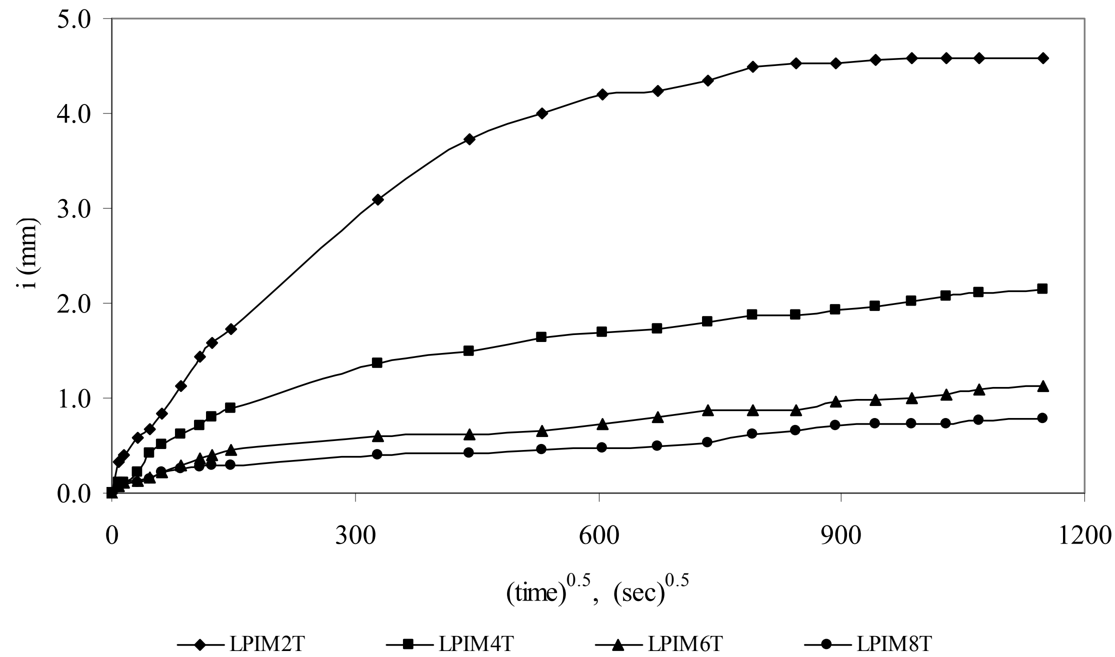

Figure 54 Typical sorption profiles

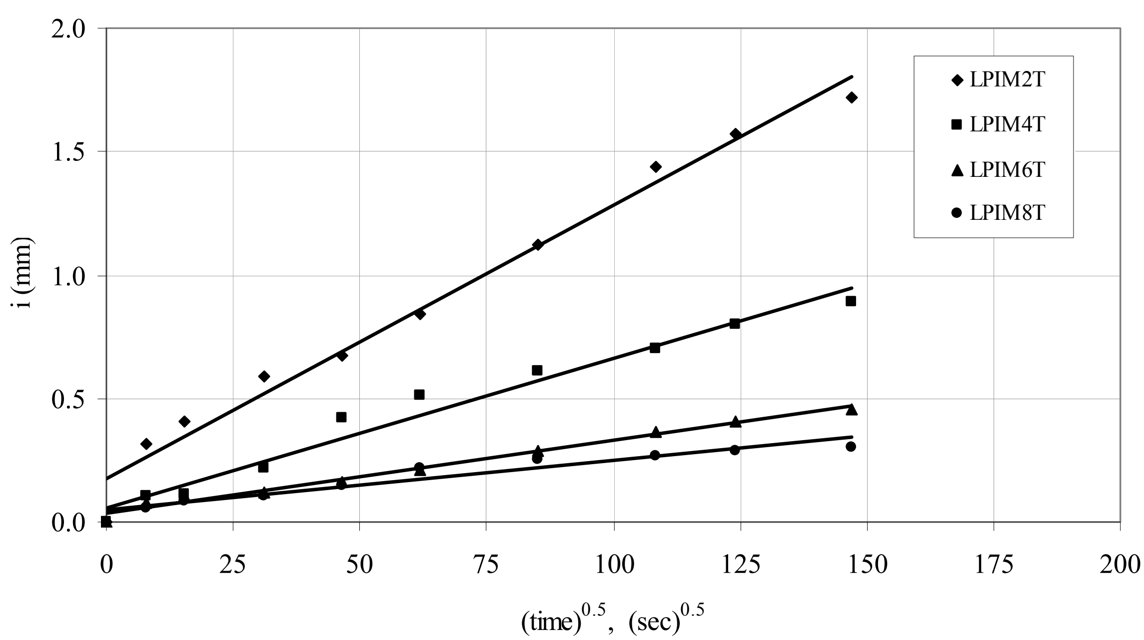

Figure 55 Initial sorption profiles

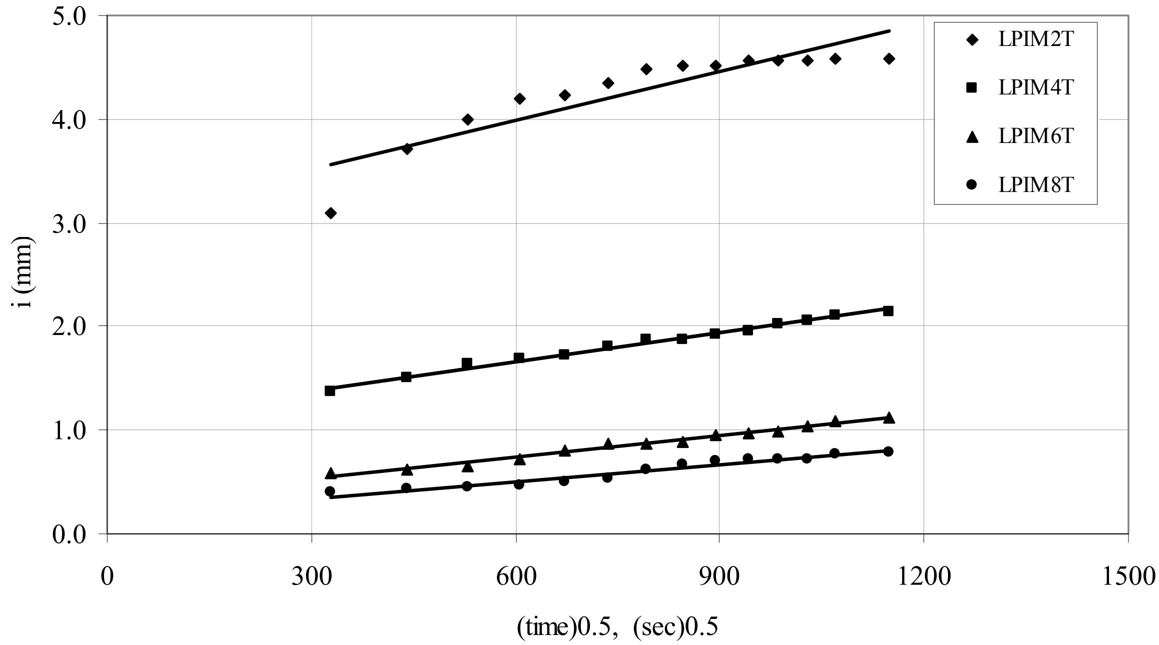

Figure 56 Secondary sorption profiles

Two types of sorptivity coefficients are defined in this paper in accordance with ASTM C 1585. Initial sorptivity (S_i) is defined by taking the slope of water uptake against the square root of time plot for the first six hours, while the secondary sorptivity (S_s) is defined by taking the slope of water uptake against the square root of time plot from the age of 1 day to 15 days or end of the test. These values need not necessarily represent the complete regime of initial linearity in all mixes. Figure 57 shows the values of sorptivity coefficients for comparative mixes. Again it can be observed that the sorptivity decreases with the increase in cement content. Further to this, the T-samples showed higher sorptivity coefficients than the corresponding B- samples. This can be understood from the fact that the top surface represents a finished surface and is relatively more porous (and hence having higher capillary voids) than the bottom surface, which in this case is in contact with a much flatter surface-cylinder base. The sorptivity coefficient of top surface will also depend on the curing regimen apart from the compaction characteristics. In addition to this, air entrainment in concrete leads to increase in the sorptivity coefficient in general, except for the leaner mixes with cement content of 150 kg/m^3 and below. This can be understood from the fact that the entrained air (and compaction voids in this material) imparts disconnectedness of the capillary network leading to an increase in the volume of absorbed water and also the rate at which it is absorbed. This fact has been observed by earlier researchers [6] as well. In case of leaner mixes, the process of air entrainment itself is very difficult and hence comparable or higher results are obtained for non-air entrained concrete. The S_s values represent relatively more stable and long-term water uptake values. For the current study the S_s values ranged from 8.7 to 36 % of S_i values depending on the mix. Lower values were observed for leaner mixes, while higher values were obtained for richer mixes, thus showing lesser changes in the short-term and long-term water uptake by richer mixes.

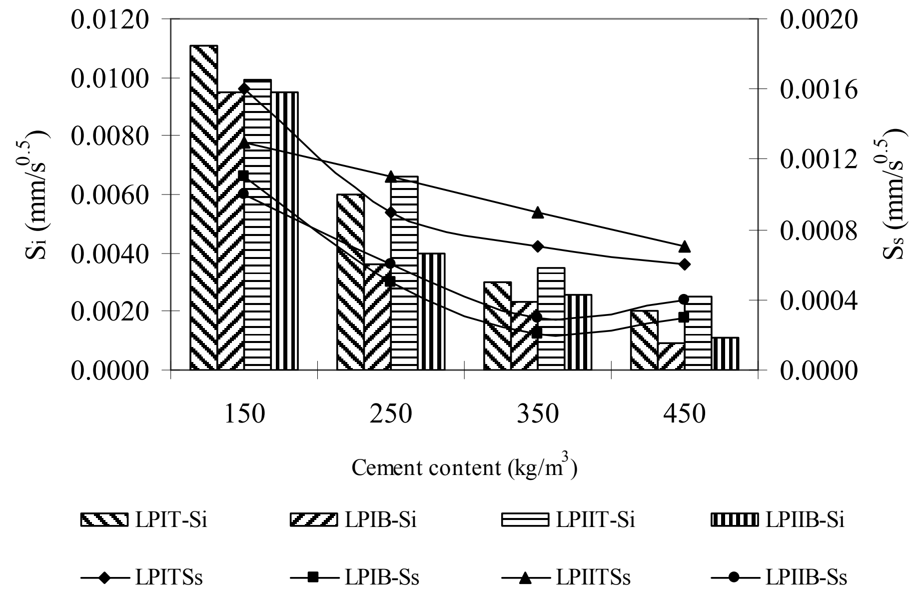

Figure 57 Sorptivity and air content

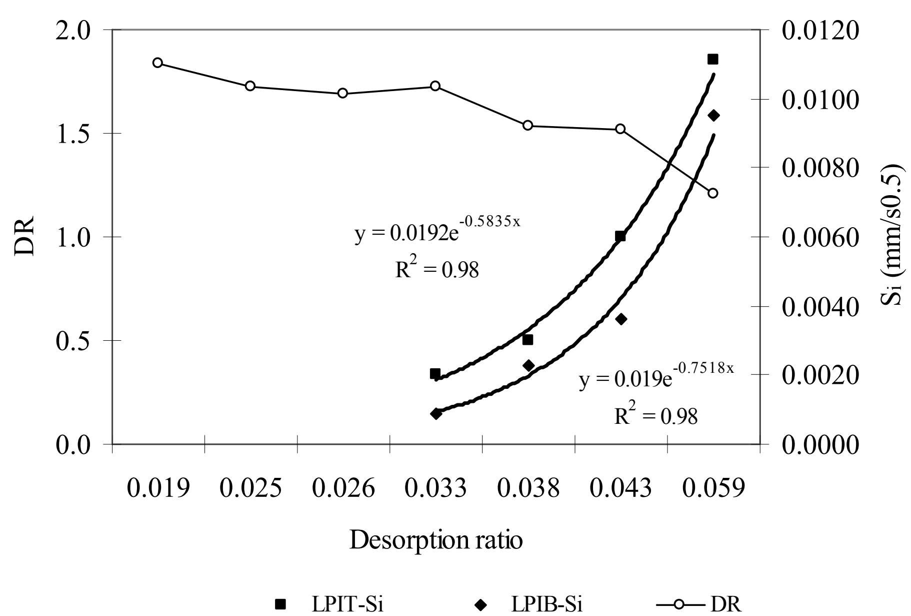

Figure 58 Dryness ratio, sorptivity and desorption ratio

Figure 58 represents the relationship between S_i and desorption ratio. Similar data has been presented in literature [10, 11] .Previous researchers have proposed polynomial relationships between these two parameters, while in the current study the authors would like to propose exponential relationship with R-squared values close to unity. This relationship shows that sorptivity coefficients increase as desorption ratio increases and this can be understood from the ease of saturating the sample. Higher desorption ratio implies relatively easier loss of water or saturated condition, which in turn also means higher capillary porosity and hence higher sorptivity.

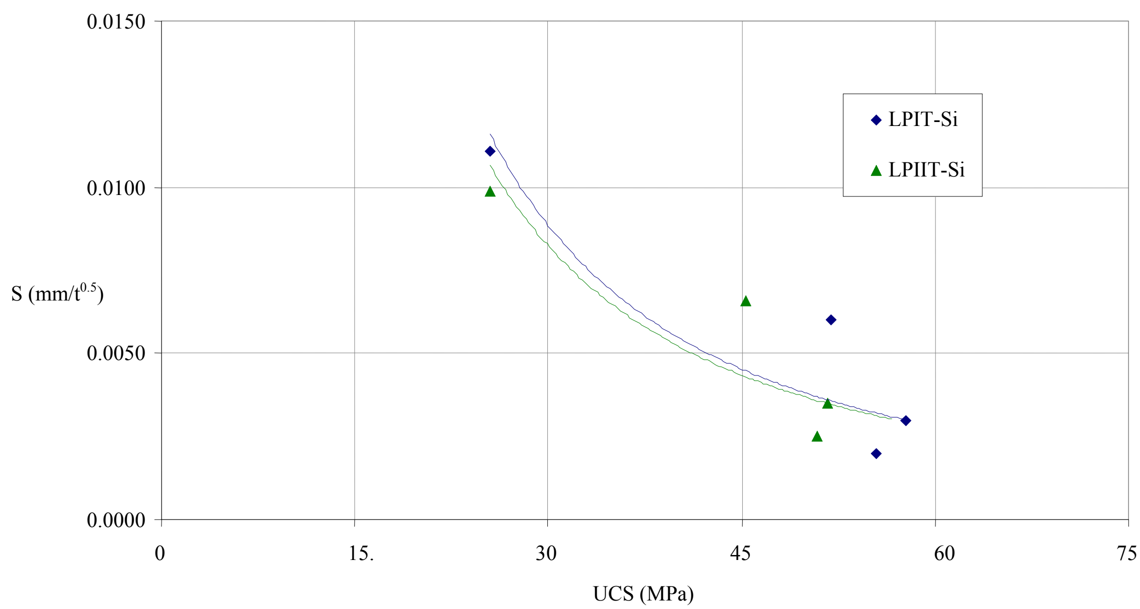

Figure 59 Water intake and compressive strength

From the trend shown in Figure 59, it can be seen that the coefficient of sorptivity decreases as the cement content of the mixes increases. In addition to this the sorptivity coefficients for the air entrained mixes were lower than the corresponding mixes not incorporating any air entraining agents. Same trend exists for the remaining samples.

4.2.10 Freeze-thaw resistance

Table 26 Theoretical and Predicted static and dynamic moduli

Phase	Mix	Density (kg/m^3)	m_c (kg)	C (Ns^2kgm^2)	n (Hz)	UCS (MPa)	E_s (GPa)	E_d (GPa)	E_d/E_s
LPI	LPIM1	2385	2.903	1534.45	2062	14.78	20.79	18.94	0.911
	LPIM2	2425	2.951	1534.45	2227	25.46	25.09	22.45	0.895
	LPIM3	2450	2.982	1534.45	2352	40.05	29.19	25.32	0.867
	LPIM4	2500	3.043	1534.45	2486	51.88	32.53	28.86	0.887
	LPIM5	2520	3.067	1534.45	2650	55.76	33.64	33.06	0.983
	LPIM6	2490	3.031	1534.45	3030	57.74	33.39	42.70	1.279
	LPIM7	2470	3.006	1534.45	2888	57.76	32.99	38.48	1.167
	LPIM8	2480	3.018	1534.45	2841	55.46	32.79	37.39	1.140
LPII	LPIIM2	2410	2.933	1534.45	2173	25.50	24.87	21.26	0.855
	LPIIM4	2536	3.087	1534.45	2425	45.32	31.92	27.84	0.872
	LPIIM6	2518	3.065	1534.45	3069	51.64	32.84	44.28	1.349
	LPIIM8	2430	2.958	1534.45	2868	50.90	30.99	37.33	1.205

Table 26 gives the estimates of the static and dynamic moduli for different mixes. The static moduli are calculated using strength-density dependent formula derived by Pauw [12] using non-orthogonal regression analysis

$$E_s = 0.0736\rho^{1.51}(f_c)^{'0.3}$$

Where,

Es is the static modulus of elasticity

P is the density of concrete

f_c' is the compressive strength of concrete

The dynamic moduli (E_d) were estimated using the formula given by ACI C215. In these calculations, the measured densities of concrete mixes were used with constant diameter (0.074 m) and height (0.286m) for all the mixes. The ratios E_d/E_s indicate that for lower cement content mixes the predicted E_d is lower than E_s while the case reverses for higher cement content mixes.

Table 27 shows the frequency measurements of the extracted cores for the F-T testing while Table 28 shows the relative dynamic moduli of the mixes. Initial readings were taken at more frequent intervals to characterize the loss of integrity of concrete mixes with lower paste contents. At later ages, the frequencies were reduced. In general, a mixed behavior for the F-T resistance is shown. One of the crucial factors that played a deterministic role in deciding the potential abilities of concrete mixes were the exposed and fractured aggregates. Here the word exposed means without any cement paste coating over it and the word fractured means cut in the process of core extraction. This is usually not the case in practice and research, where special specimens are prepared for this testing. Considering the uniqueness of these specimens it was preconceived that a genuine comparison with the existing body of knowledge would be inconsistent, yet more representative of the true response of concrete vis-à-vis its void structure resulting due to the simulation of lesser confined casting of concrete. Figure 60 shows the exposed and fractured aggregates at the core surface.

For Phase-I mixes different responses were observed for different mixes. Leaner mixes showed very poor performance as was expected. With the increase in the cement content the performance of the mixes improved but the resistance to F-T was not appreciable. With the strongest of the mixes demonstrating a relative dynamic modulus of just over 80% at the end of 300 cycles, it could easily be deduced that even the richer mixes would not last for more than 600 number of F-T cycles considering a linear drop in the integrity of mixes.

It is worth noting that the disintegration of these mixes took place through a combined action of failure of aggregates and the cement paste. The aggregates used were oolites, which are rated as 1 to 2 on a scale of 5 for durability, which means they are poor in performance. In addition to this the aggregates may also influence the role of water in the binder or penetration of moisture and the atmosphere deeper into the concrete, than desirable. Some of the petrological characteristics of aggregates that influence its F-T performance are compactness, porosity, texture and micro-fractures. In addition to this the micro-porosity of aggregates, their volumetric stability, dust producing nature and susceptibility of allowing the cracks due to F-T testing to penetrate deeper inside the concrete also influences the overall response of the concrete to F-T loading. Another important issue is the softening of weak and porous aggregates when wetted [13].

Figure 60 Modes of failures due to F-T loading

Cement paste homogeneity is another requirement for better F-T resistance of concrete. It is well established that the cement paste in RCC mixes is highly heterogeneous. This leads to the inclusion of more anisotropy of the material.

Figure 61 shows the relative dynamic modulus (P_c) of these mixes at the end of different F-T loading cycles for LPI series. In LPI mixes, which were not air entrained, the performance in response to rapid F-T was variable. Mixes with lower cement contents showed very poor performance, with M1, 2 and 3 lasting for just over 60, 100 and 125 cycles. Although the performance of the mixes increased with the cement content, these lower cement content mixes need further optimization. Only mixes that lasted for 300 cycles were the M5 and above mixes.

Similar trend is obtained for LPII mixes with a relatively little better performance of all the mixes (Refer to Figure 4-23). These trends are shown in Figure 62. While Figure 63 represents the relative values of P_c for corresponding mixes at the end of the tested number of cycles. It can be seen that the air entrained concrete showed some improvement in its performance but not to a great extent.

Table 27 Average fundamental frequencies for F-T loading cycles

Phase		LPI								LPII			
Mix	Cycles	LPIM1	LPIM2	LPIM3	LPIM4	LPIM5	LPIM6	LPIM7	LPIM8	LPIM2	LPIM4	LPIM6	LPIM8
Fundamental Transverse frequency (Hz) at the end of X cycles	0	2062	2227	2352	2486	2650	3030	2888	2841	2173	2425	3069	2868
	10	1950	2219	2345	2463	2596	3058	2871	2855	2131	2497	3063	2882
	25	1905	2207	2321	2459	2603	3035	2877	2846	2102	2435	3072	2885
	35	1786	2112	2233	2425	2598	3023	2860	2845	2047	2374	3053	2887
	68	1560	2010	2097	2365	2527	2994	2830	2808	1905	2266	3048	2857
	101	1122	1851	1997	2267	2464	2977	2796	2693	1656	2181	3027	2864
	132	NA	1553	1791	2192	2430	2918	2726	2637	1503	2224	3029	2875
	165	NA	1392	1595	2065	2312	2904	2692	2544	1436	2175	3019	2845
	200	NA	NA	1412	1988	2237	2863	2646	2516	NA	2106	3004	2828
	232	NA	NA	NA	1938	2209	2766	2579	2461	NA	1972	2975	2797
	265	NA	NA	NA	1878	2204	2730	2533	2450	NA	1855	2967	2818
	300	NA	NA	NA	1783	2139	2729	2479	2393	NA	1885	2947	2765

Table 28 Average relative dynamic moduli during F-T cycling

Phase		LPI								LPII			
Mix	Cycles	LPIM1	LPIM2	LPIM3	LPIM4	LPIM5	LPIM6	LPIM7	LPIM8	LPIM2	LPIM4	LPIM6	LPIM8
Relative dynamic modulus of elasticity (RDME), w.r.t. no of cycles	0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	10	89.5	99.3	99.3	98.2	96.0	101.9	98.9	101.0	96.2	105.9	99.6	101.0
	25	85.3	98.2	97.4	97.8	96.5	100.3	99.3	100.3	93.5	100.9	100.2	101.2
	35	75.0	90.1	90.1	95.1	96.2	99.5	98.1	100.3	88.7	95.9	99.0	101.3
	68	57.3	81.5	79.5	90.5	91.0	97.6	96.1	97.7	76.8	87.4	98.7	99.2
	101	29.7	69.1	72.1	83.1	86.5	96.5	93.7	89.8	58.0	81.0	97.3	99.8
	132	0.0	48.7	57.9	77.8	84.1	92.7	89.1	86.1	47.8	84.2	97.4	100.5
	165	0.0	39.1	46.4	69.0	76.1	91.8	86.9	80.2	43.6	80.5	96.8	98.4
	200	0.0	0.0	36.1	64.0	71.2	89.2	84.0	78.4	34.8	75.5	95.8	97.3
	232	0.0	0.0	0.0	60.8	69.5	83.3	79.8	75.0	0.0	66.1	94.0	95.1
	265	0.0	0.0	0.0	57.1	69.2	81.2	77.0	74.4	0.0	58.5	93.5	96.6
	300	0.0	0.0	0.0	51.4	65.2	81.1	73.7	70.9	0.0	60.5	92.2	92.9

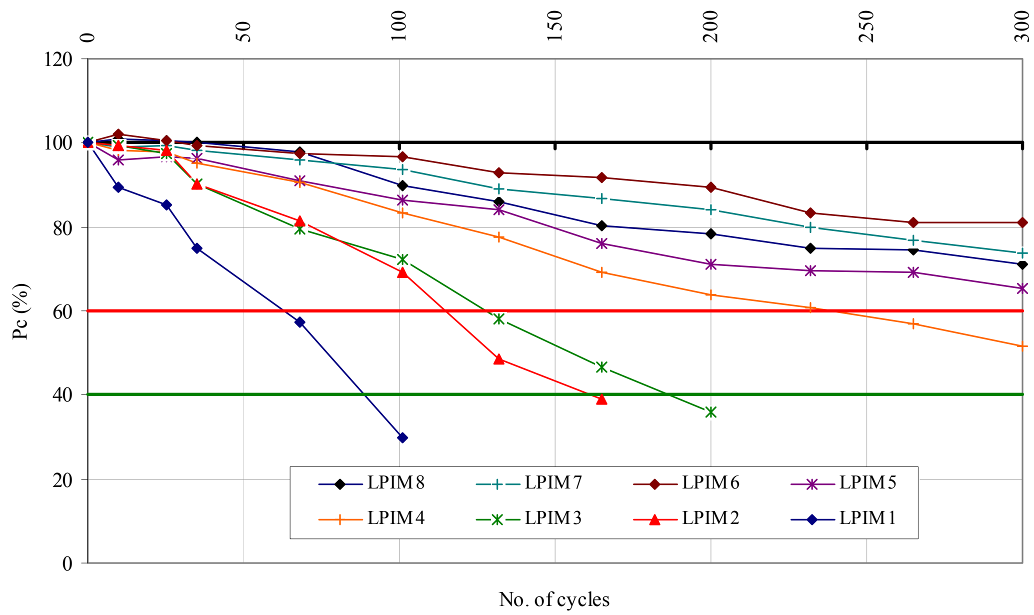

Figure 61 Relative dynamic modulus for LPI mixes after cyclic loading of F-T samples

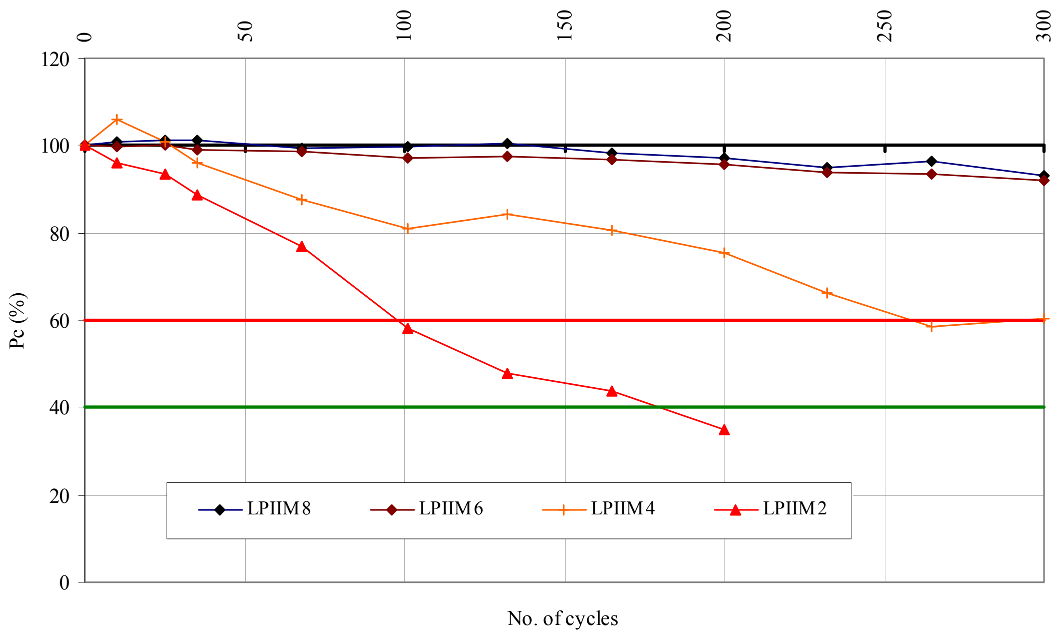

Figure 62 Relative dynamic modulus for LPII mixes after cyclic loading of F-T samples

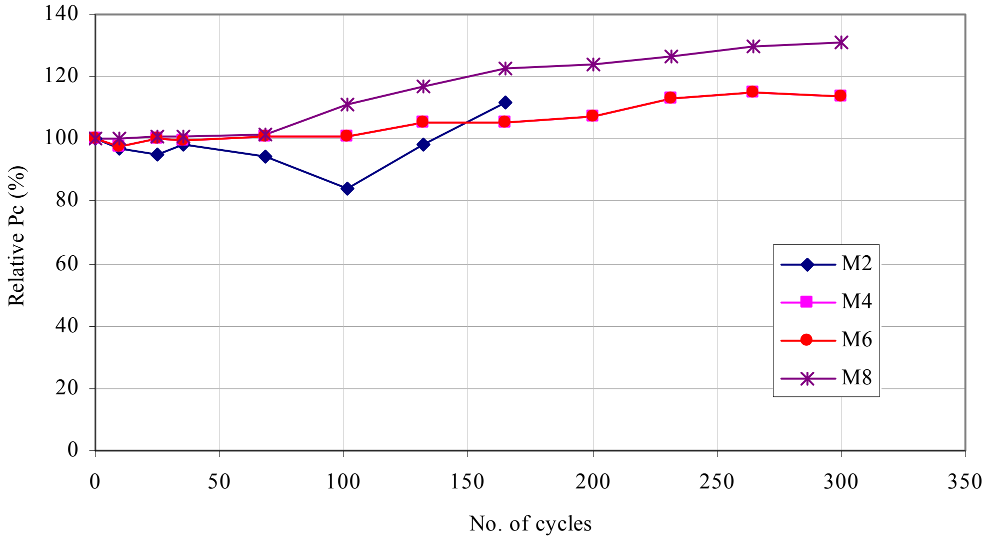

Figure 63 Relative Pc values for limestone mixes

It is known that the freezing cycles in water tend to increase the degree of saturation of concrete and is more important in relatively drier concrete like RCC. One of the possible causes of the lack of resistance of RCC to accelerated F-T testing could be the gradual filling up of capillary pores and some of the compaction pores. During the testing or in real life the small number of compaction voids gets filled up with water and are surrounded by entrained air voids. As water freezes, it tries to find escape routes and can reach out only to those voids that are close enough thus leading to creation of localized flow of water which is much higher than the flow from the capillary pores to the air bubbles in normal concrete.

Another aspect of poor F-T resistance is the heterogeneity of the cement paste. It can be seen from Figure 64 that the cement paste contains large amount of micro-cracking after 28 days of curing. In addition to this the aggregate-paste zone also shows distinct cracking and appears to be more porous in than the conventional concrete.

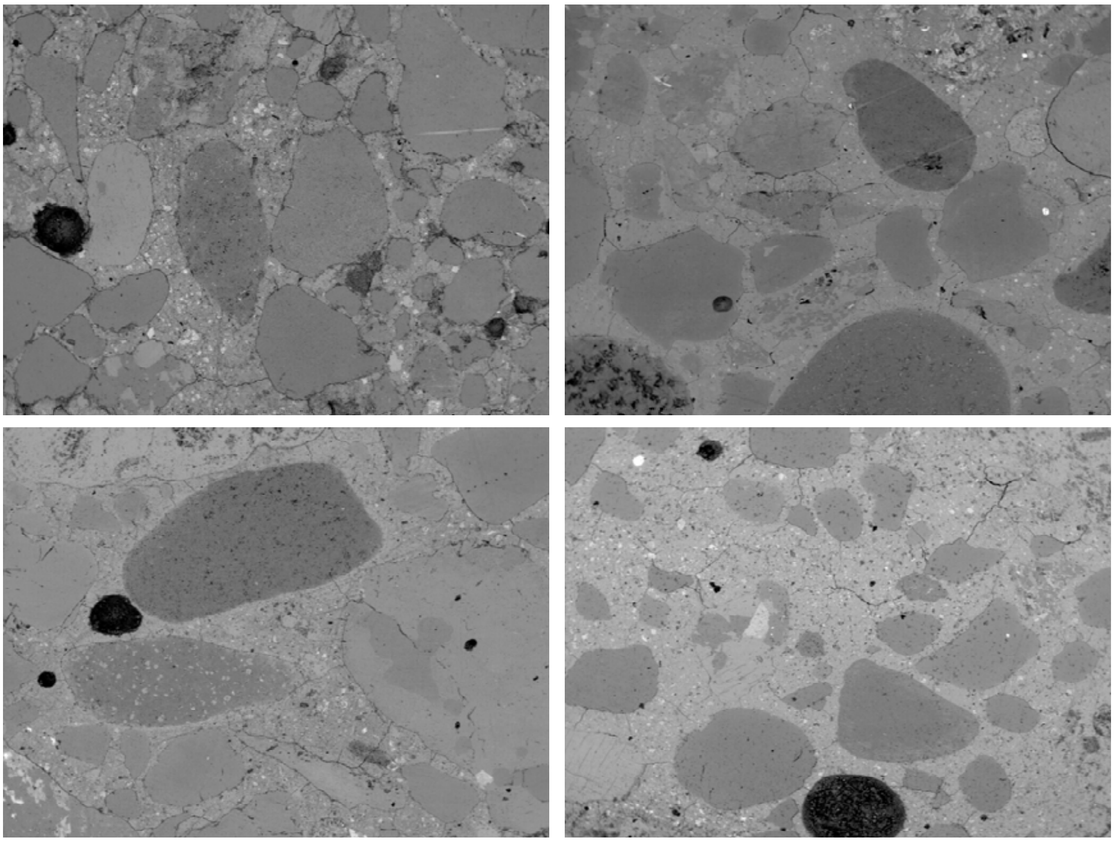

Figure 64 SEM images taken at 40x for LPI-M2, -M4, -M6 and M8 mixes

Some of the cracks ran from one aggregate to the other while there were some cracks that were radially oriented from the boundary of the aggregates. A significant number of images showed the cracks to be parallel to the top/bottom face of the concrete. Considering the available evidences the following hypothesis could be considered to be as the probable cause(s) of failure against F-T cycling of concrete:

1. Drying shrinkage could have happened at early ages of concrete leading to a very poor aggregate-paste bond. Higher porosity of this phase could lead to higher water transport along this zone. This was evident from the fact that initially intact aggregates were spalling off. Drier and leaner the mix, weaker would be this bond

and thus more porous and permeable leading to localized failure eventually leading to full sample failure,

2. The nature of compaction provided to these samples during their formation is a cyclic impact loading parallel to the top and bottom faces of concrete. One of the possible reasons for appearance of random and radially oriented cracks could be explained on the basis of the method of compaction used in these mixes. One of the possible reasons for the appearance of these cracks could be the local compression and rarefaction of this dry concrete-RCC.
3. One of the reasons that could lead to the cracks spanning from one aggregate to the other could be understood from the perspective of water absorption of the limestone. The water absorption value for this olitic limestone is about 3.5%, which is comparatively higher and means that the aggregates' water demand could be competing with the water demand of the cement hydration leading to shrinkage cracking.
4. The method used for sample preparation was coring of beams. This method of sample extraction lead to complete exposure of aggregates and at times to the fracturing of aggregates, thus providing a pathway to the ingress of water into the concrete. Further to this, this method lead to samples without any finishing cement paste coating to the aggregate skeleton, thus rendering these samples results less comparable to the available database.

4.2.11 Air void analysis

Using the images obtained from the scanning electron microscope analyses were carried out for the air voids content of the mixes. Figure 65 shows the trends of the air voids' distribution in the concrete systems with different cement and paste systems. It can be clearly seen the air can be entrained in dry mixes of RCC. The amount and distribution would depend on materials' composition, the compaction energy and level of confinement.

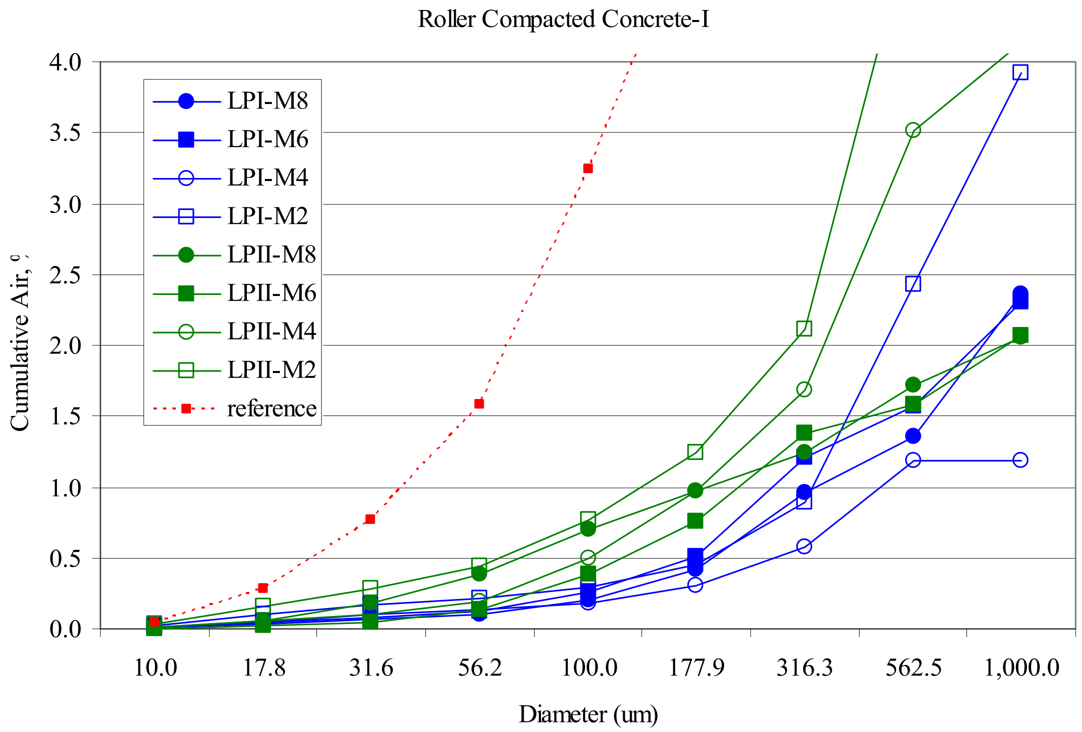

Figure 65 Variation of air voids' content and distribution with air entrainment and cement content

It can be seen from the results of these analyses that it is possible to entrain air even while mixing in a small tilting drum mixer. The amount of air entrainment is relatively less in lower cement content mixes when compared with the higher cement content mixes. The analytical treatment of the nature of these curves is considered to be beyond the scope of this work.

Synopsis

In view of the obtained results in the form of fresh, mechanical and durability characteristics of the RCC mixes under study, it was observed that RCC mixes with lower cement contents can be applied for pavement applications like pavement bases and shoulder bases. Richer mixes can be applied for wearing courses. These studies need further investigations for specialized applications. The working curve developed in this study indicates that after a certain w/c ratio and at higher cement content the normal relationship between the compressive strength and w/c ratio is not observed, instead a deviation exists due to not optimizing the compaction effort. Bulk properties like the permeable voids, water absorption and densities showed an optimizing behavior in terms of the trend they follow w.r.t. the cement content. Sorptivity and desorptivity showed an improving behavior with the increase in the cement content. Considering the nature of the samples used for F-T testing, it is difficult to derive comparative conclusions, yet a clear trend is shown in the behavior of the mixes. With increasing cement contents, the F-T resistances of the mixes increased unto a certain cement content and then showed a decreasing behavior. Air entrainment is possible in richer RCC mixes, and to a certain extent in leaner mixes.

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5. SUMMARY OF CONCLUSIONS AND FUTURE RESEARCH

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5.3 Recommendations for future research 143

5.1 General conclusions

In synopsis, the project covered a very wide range of cement contents potent of applications ranging from shoulder bases to wearing course. The following general conclusions can be derived from this research

1. With the increase in the cement content, the MDD and the strength of the RCC mixes increase, reaches an optimum value and starts dropping down. This happens due to un-optimized compaction effort provided to concrete. Different compactibilities are provided by concrete with different mix proportions. Optimization of compaction effort taking the cognizance of the mix constituents would lead to a better compaction and hence strength.
2. This variation of strength and density is reflected in other properties of the RCC mixes. Hence controlling the density with proper optimization of compaction efforts is necessary. Air entrainment in these mixes showed nominal change in the density while there was a slight drop in the compressive strengths in higher cement content mixes.
3. The water absorption and permeable voids content of the mixes showed a similar optimization behavior. Air entrainment has no significant effect on the water

absorption value of corresponding mixes. Estimating permeable voids content with same amount of boiling time seems to be inadequate for finding out the permeable voids content of the mixes. Other methods might be able to provide a better perspective over this matter.

4. Sorptivity profiles and sorption plots can be used for predicting the uptake behavior of RCC. The physics of water movement can be predicted once a correlation between the coefficient of sorptivity and compressive strength are derived.
5. Freeze-Thaw resistance of RCC mixes cannot be directly predicted from the tests conducted in this research. It was because the degradation of exposed-aggregate cored samples under the composite hydro-thermal loading was relatively rapid.
6. SEM images indicated that the paste in RCC mixes is very heterogeneous with a relatively poor aggregate-paste inter-phase and severe internal cracking, the investigation of the causes of which are beyond the scope of this research.
7. Air entrainment enhanced the laboratory performance of the mixes. Air entrainment is possible in RCC mixes mixed in tilting drum laboratory mixer, but a relatively high amount of dosage of air entraining agent is required. Mixes with lower cement content are difficult hosts for air entraining agent, but cement rich mixes are easier for air entrainment.

5.2 Contributions to the State-Of-the-Art

This comprehensive study covers a wide range of cement contents in RCC for various pavement applications. Following are the state-of-the art contributions of this study:

1. For the first time, such a wide range of cement contents have been studied with special attention provided for proportioning the mixes for pavement applications. This has generated a parent database for further studies exploring the possibilities of applications of RCC in pavements.
2. The variation of bulk properties of the mixes covering a range of compressive strength would help understand the variations in behavior of the mixes in response to particle packing and characterization for porosity-voids related properties. Water absorption can be used as a parameter for specifying RCC.
3. The sorptivity and desorptivity behavior of RCC mixes covering such a wide range of cement contents has been explored for the first time. The desorptivity behavior represents the draining ability of the mixes and shows how quickly and effectively can the mixes be drained. Moreover the dryness ratio as defined in this study can further be utilized for accessing the relative susceptibility of the mixes to give up water. Sorptivity behaviors, both initial and secondary can be utilized in defining the water uptake behavior of the mixes and thus in understanding the water transport phenomenon in RCC mixes. This will also help comprehend rate at which RCC mixes get saturated and become susceptible to damage via F-T actions.
4. F-T results opened up new questions related to the reliability and authenticity of the extracted specimens or the sample preparation method to be used for tests related to water transport behavior of concrete mixes. The current results show that it is possible to entrain air in concrete using a drum mixer and this air influences the compressive strength and the F-T response of the mixes. From the available data, it can be concluded that air entrainment leads to enhancement of the F-T resisting ability of RCC mixes for comparable cement contents.

5. SEM analysis was used on a large scale to judge the distribution of entrained air in RCC mixes. This analysis helped analyzing the nature of the cement paste and the microstructure of mixes.
6. In addition to this the air void analysis was done using the SEM images. This helped predict the nature of air void size distribution in RCC mixes.

5.3 Recommendations for future research

This study has raised many questions, which could be used for furthering the body of knowledge related to this subject. These are enlisted as follows:

1. Optimization process for the compaction amount of compaction energy and its configuration need to be well defined. Without the definition of such basic parameters, it will be difficult to produce comparable results.
2. Further investigations are required to determine the microscopic processes underlying the macroscopic anomalous diffusion for water infiltration
3. Application of sorption and desorption data in predicting the Freeze-Thaw performance of concrete is essential. This data is not available either in the empirical form or otherwise. Statistical studies specifically pertaining to understanding of such behavior would lead to a better understanding of the durability of concrete.
4. Studies on the ITZ development in RCC do not exist in literature. Undoubtedly, this zone has a strong influence on the hydraulic conductivity of concrete and thus would determine the nature of deteriorating mechanism due water transportation.
5. Studies related to three dimensional imaging techniques like computed tomography (CT) can be utilized for further analyzing the spatial distribution of

the air voids. These studies can also be used in modeling the air void distribution, thus helping in understanding and predicting the mean size and spacing of the air voids.

6. Optimization studies with various admixtures would lead to a better understanding of the rheology and/or shearing behavior of the RCC mixes. This would further facilitate the understanding of the laying and compaction processes of RCC.

Appendices

Appendix A: ASTM Standards

C 29-97	Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate
C 33-01	Standard Specification for Concrete Aggregates
C 39-01	Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
C 42-99	Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
C 70-01	Standard Test Method for Surface Moisture in Fine Aggregate
C 125-00	Standard Terminology Relating to Concrete and Concrete Aggregates
C 127-01	Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate
C 128-01	Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate
C 131	Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine
C 136	Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates
C 172-99	Standard Practice for Sampling Freshly Mixed Concrete
C 192-00	Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory
C 215-97	Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Frequencies of Concrete Specimens
C 260-00	Standard Specification for Air-Entraining Admixtures for Concrete
C457-06	Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete
C 494-99	Standard Specification for Chemical Admixtures for Concrete
C 511-98	Standard Specification for Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes
C 535-96	Standard Test Method for Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine
C 617-98	Standard Practice for Capping Cylindrical Concrete Specimens
C 642-97	Standard Test Method for Density, Absorption, and Voids in Hardened Concrete
C 666-97	Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing
C 702-98	Standard Practice for Reducing Samples of Aggregate to Testing Size
C 778-00	Standard Specification for Standard Sand
C 943-96	Standard Practice for Making Test Cylinders and Prisms for Determining Strength and Density of Preplaced-Aggregate Concrete in the Laboratory

C 1064-99	Standard Test Method for Temperature of Freshly Mixed Portland Cement Concrete
C 1170-91	Standard Test Methods for Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table
C 1252-98	Standard Test Methods for Uncompacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, and Grading)
C 1435	Standard Practice for Molding Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Hammer
C1585-04	Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes
D 75-97	Standard Practice for Sampling Aggregates
D 448-98	Standard Classification for Sizes of Aggregate for Road and Bridge
D 558-96	Standard Test Methods for Moisture-Density Relations of Soil-Cement Mixtures
D 1557	Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort
D 3398-00	Standard Test Method for Index of Aggregate Particle Shape and Texture
D 4791-99	Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate
E 11-01	Standard Specification for Wire Cloth and Sieves for Testing Purposes Measurements
IEEE-ASTM-SI-10	Standard for Use of the International System of Units (SI): The Modern Metric System

Appendix B: AASHTO Standards

M 6-93 (1997)	Fine Aggregate for Portland Cement Concrete
M 43-88 (1999)	Sizes of Aggregate for Road and Bridge Construction
M 80-87 (1999)	Coarse Aggregate for Portland Cement Concrete
M 85-00	Portland Cement
M 92-96	Wire-Cloth Sieves for Testing Purposes
M 154-00	Air-Entraining Admixtures for Concrete
M 201-00	Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes
M 231-95 (1999)	Weighing Devices Used in the Testing of Materials
T 2-91 (1996)	Sampling of Aggregates
T 11-91 (1996)	Materials Finer than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing
T 19-00	Bulk Density ("Unit Weight") and Voids in Aggregate
T 22-97	Compressive Strength of Cylindrical Concrete Specimens
T 23-97	Making and Curing Concrete Test Specimens
T 24-97	Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
T 26-79 (1996)	Quality of Water to be Used in Concrete T 27-99 Sieve Analysis of Fine and Coarse Aggregate
T 84-00	Specific Gravity and Absorption of Fine Aggregate
T 85-91 (1996)	Specific Gravity and Absorption of Coarse Aggregate
T 96-99	Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine
T 103-91 (1996)	Soundness of Aggregates by Freezing and Thawing
T 119-99	Slump of Hydraulic Cement Concrete
T 126-97	Making and Cuing Concrete Test Specimens in the Laboratory
T 134-95	Moisture-Density Relations of Soil-Cement Mixtures
T 141-97	Sampling Freshly Mixed Concrete
T 157-00	Air-Entraining Admixtures for Concrete
T 161-00	Resistance of Concrete to Rapid Freezing and Thawing
T 210-96	Aggregate Durability Index
T 231-97	Capping Cylindrical Concrete Specimen
T 248-96	Reducing Samples of Aggregates to Testing Size
T 304-96	Uncompacted Void Content of Fine Aggregate
T 309-99	Temperature of Freshly Mixed Portland Cement Concrete

Appendix C: Unit Conversions

Quantity	From English Units	To Metric Units	Multiply by
Length	mile	km	1.609347
	yard	m	0.9144
	foot	m	0.3048
	inch	mm	25.4
Area	square mile	km^2	2.59
	acre	m^2	4047
	acre	hectare	0.4047
	square yard	m^2	0.8361
	square foot	m^2	0.092 90
	square inch	mm^2	645.2
Volume	acre foot	m^3	1 233
	cubic yard	m^3	0.7646
	cubic foot	m^3	0.028 32
	cubic foot	L (1000 cm^3)	28.32
	100 board feet	m^3	0.236
	gallon	L (1000 cm^3)	3.785
Mass	lb	kg	0.4536
	kip (1000 lb)	metric ton (1000kg)	0.4536
Mass/length	plf	kg/m	1.488
Mass/area	psf	kg/m^2	4.882
Mass density	pcf	kg/m^3	16.02
Force	lb	N	4.448
	kip	kN	4.448
Force/length	plf	N/m	14.59
	klf	kN/m	14.59
Pressure	psf	Pa	47.88
	ksf	kPa	47.88
	psi	kPa	6.895
	ksi	MPa	6.895
Moment of force	ft-lb	N.m	1.356
	ft-kip	kN.m	1.356