High Performance Self-Consolidating Cementitious Composites

Ganesh Babu Kodeboyina

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Preface

The improving urbanization standards forced the construction industry to look for not only the most economical of the construction materials but also avenues to ensure high performance, necessitating a significant transformation in its outlook. Self-consolidating concretes brought about a lasting change in the construction setup, even if it was only by tweaking some of the existing materials, design, and production methodologies already well known to the industry.

High Performance Self-Consolidating Cementitious Composites attempts to bring together some of the basic intricacies in the production of the complete range of self-consolidating cementitious composites, with a proper understanding of the contributions of different materials and their combinations. To the discerning reader the two fundamentals aspects - the modulation of rheology of cementitious materials paste through superplasticizers and viscosity-modifying agents, and the interaction of this paste phase with filler components like coarse and fine aggregates - to ensure a self-compacting mass are explained. Also, it was presumed a priori that given the higher fines content and the self-compactability for ensuring a defect-free structure and recognizing the fact that additional fines are generally supplemented through materials like fly ash, the resulting concrete will automatically be of high performance. However, there is a need to understand the pore filling and pozzolanic effects of the powders and the different supplementary cementitious materials in vogue appropriately, to ensure that both the strength and the performance could be adequately predicted, which is also explained in detail herein.

Another important factor that is probably not fairly conspicuous and is often overlooked is that with the limited budgetary provisions available for most research efforts, even in prestigious research laboratories and educational institutions, coupled with the limited time and manpower available, studies in general are limited to specific targets in each case. An overarching program of research, like the "Concrete in the Oceans" program of the United Kingdom, will need support for over a decade with several specific aspects looked at by different institutes to ensure a realistic and comprehensive understanding. However, there are a lot of efforts directed toward different goals by several members of the research community. Now, the other way to find a solution for this problem was to comprehensively put together these diverse research efforts of the different investigators, identify the broad fundamentals underlying the different aspects of the problem, and systematically analyze the information to arrive at a more holistic understanding. This approach, more easily said than done, needs a compilation of the available results into a data platform; it also needs categorization of the results

under acceptable scientific criteria through earlier experience, and finally we can arrive at broad guidelines for an appropriate understanding of the problem. In line with this, an effort was made in this book to compile a large database on self-compacting concretes from the literature, categorize them to represent specific groups, and suggest methods for arriving at self-compacting concretes with a wide range of materials and over a wide range of consistencies. Apart from this, *High Performance Self-Consolidating Cementitious Composites* tries to look at the performance and limitations of this regime of concretes and suggests methods to address some of these appropriately. Naturally, in some cases a few of the aspects discussed were based only on the limited information available from the earlier investigations and may have to be verified before extending them to reflect the behavior of the entire spectrum of self-compacting concretes.

The fact that it is not possible to summarize even partly the volume of information available from various conferences, seminars, and publications available on a topic that has generated an enormous amount of interest in the research and development community as well as the construction industry was well recognized. Naturally, the basic idea was to only highlight the critical parameters and interactions between these parameters to ensure the production of high-performance, self-consolidating cementitious composites with greater confidence. The second aspect was to collate a relevant group of concretes in each particular case and put together a series of ready reckoner charts to have a guideline for arriving at an appropriate self-consolidating cementitious composite of choice. Finally, it was attempted to present briefly the relationships between various green and hardened state characteristics. *High Performance Self-Consolidating Cementitious Composites* also presents a broad outline of the present state of the art, in terms of the different national recommendations and codal provisions, the views and perceptions of the industry, along with an insight into the basic materials technology. Specifically, some of the graphs (nomograms) could help the practicing engineers on-site to understand and modulate the concrete composites being produced directly. Thus, instead of summarizing the information available in literature, the book envisages to be a tool for explaining the basic relationships and the interactions between the constituents to assist students, researchers, and industry professionals.

Acknowledgments

Self-consolidating concrete has attracted the attention of both the industry and the research community because of the ease of placement and time saved in concreting operations. Naturally, this prompted several efforts toward the design, production, and placement of the material. A critical and explicit understanding of the insights into any such concrete requires understanding of the contributions from several earlier researchers on the various facets that originally resulted in the development of the high-performance cementitious composites of today. I heavily relied on the wealth of knowledge that originated from North America and, more importantly, Europe in the attempts to present the topic in my own perspective. Many of the concepts that are discussed and elaborated in these pages have in the background the several discussions I had with these researchers, teachers, and students, even if some of them were not directly related to the making of this book.

At the very outset, I should thank profusely all my teachers starting from school to the point of obtaining my doctorate as well as several other professional colleagues who always encouraged me in my efforts to just learn. It is only appropriate to acknowledge the fact that among several of these tall figures is the name of one distinguished personality that stands out, Prof. Dr.-Ing. P. Srinivasa Rao, Department of Civil Engineering, Indian Institute of Technology, Madras, who inculcated in me an intensely critical thinking, strict attention to detail, and persistence, being a guide and mentor during my time as his research student for my master's and doctoral programs and also later as his associate at the institute.

I also gratefully acknowledge that it was indeed an honor to be a fellow of the Alexander von Humboldt Foundation, which helped me to not only interact with several eminent professors and researchers from German universities but also helped me in learning the German language so that I can have a direct understanding of the literature published, apart from being a member of their research and social community. Some of the specific intricacies in the modifications of concrete are hidden in the earlier literature that was largely published in German, and for an individual educated in the English medium, there is limited possibility of getting to know them. During a later visit as an Indo-German fellow, I had the opportunity to be associated with Prof. Dr.-Ing. Peter Schiessl, then heading the Institut für Bauforschung, RWTH Aachen University, Aachen, working on fly ash and corrosion of steel in concrete. It was indeed this association that paved the way for the development of the concept of dual factors in cementitious efficiency of most pozzolanic admixtures, which forms the central theme of this book. I thank him with all my heart for all the long and open discussions on the several aspects of fly ash in concrete and also corrosion of steel in concrete.

Also, over the years, it was indeed a pleasure to be associated with a very large number of students, who during their research efforts inadvertently posed several questions that needed to be answered. They also participated in many ways in refining and reorienting probably some of the known facts to be put in their proper perspective. Even among this very large group of well over a hundred, I should specifically appreciate and thank the efforts of Bhojaraju ESTR Chandrasekhar, a PhD scholar, particularly for his contribution in shaping this book in the present form through his several unending objective discussions and also, more importantly, through his untiring efforts to help in processing and producing most of the graphs and nomograms into the present form that really make them stand out as the hallmark of this book.

Finally and most importantly, I express my deep sense of gratitude to my family, my wife Devi, daughter Deepti, and son Srikanth Aditya, for their love and understanding of my absence during the several academic and professional commitments over the years.

Author

Professor Ganesh Babu Kodeboyina obtained his bachelor's degree in civil engineering with distinction from the Andhra University and joined the Indian Institute of Technology (IIT) Madras for a master's degree in structural engineering. He continued at IIT Madras and obtained a doctoral degree, working in the area of behavior of partially prestressed concrete structural members. He then joined Structural Engineering Research Centre as a scientist and was involved in several projects including large diameter prestressed concrete pipes, ferro cement and fiber reinforced concrete, apart from being the principal investigator on the United Nations Development Programme (UNDP)-sponsored project on Polymer Concrete Composites. He was awarded the Alexander von Humboldt (AvH) Foundation Fellowship during this period to undertake postdoctoral research in Germany.

However, during the same period, he joined IIT Madras as a faculty member of the Department of Ocean Engineering, working in the area of ocean structures and materials in marine environment, and undertook his AvH fellowship program. After his return to Germany even while he was engaged in active research on offshore structures, with special interest, he singlehandedly developed the most successful "Structures, Materials, Applications and Rehabilitation Technologies" laboratory of the department, which he headed until retirement. Apart from being an active research worker producing more than 20 doctoral theses, and several other master's theses on the various topics related to ocean structures, and in particular on materials in marine environment, he was also a consultant to the industry on several different aspects. To mention a few, as a structural engineer, he proof-checked designs of more than 50 prestressed concrete bridges and suggested the repair strategies for another 100 bridges of the National Highway Authority of India, designed and rehabilitated several port and harbor facilities apart from damage assessment, and was involved in the rehabilitation of a large number of operating industrial structures. Even so, he was better known for his contributions to high-performance cementitious composites and was a retainer consultant to nearly all the major cement producers as well as construction chemical manufacturers in the country. In fact, he investigated the performance characteristics of almost all of the cements that were produced by these industries. Apart from this, he was a part of the UN common fund-sponsored program, and was entrusted with the evaluation of the corrosion performance of galvanized reinforcement both in the laboratory and at the Madras port field site organized by him exclusively for this purpose.

These achievements resulted in him being appointed as the director of the Central Building Research Institute (CBRI), Roorkee, a prestigious constituent

National Laboratory of the Council of Scientific and Industrial Research (CSIR) of the Government of India. It was here that, apart from other research activities as director, he undertook several rehabilitation projects, notably the rehabilitation of the only existing double shell built by the famous Prof. Kurt Billig, the very first director of the CSIR-CBRI. These efforts culminated in his being involved in several activities related to the preservation and rehabilitation of many of the centuries-old temples and also other world heritage sites in the country like the Taj Mahal, Konark, and many others, an activity close to his heart, or his premier passion.

He later returned to IIT Madras to complete his tenure at the institute and was once again involved in research and consultancy in areas of ternary cements, Ultra-High-Performance Concretes (UHPCs), and polymer composites. He also undertook a study on the residual service life and service-life extension measures of the Fast Breeder Test Reactor (FBTR). Incidentally, he was responsible for the design and testing of thermal effects on heavyweight concretes that had to be almost self-consolidating in the enclosed top shield of the Prototype Fast Breeder Reactor (PFBR). He was rated a very good teacher by several groups of students and is also passionate about fine arts, ancient texts on yoga, and temple vastu, to name a few.

1

Introduction

1.1 Concept

Concrete has been the preferred material for construction because it can be molded into any shape dictated by the structural configuration requirements while being the most economical. Cementitious composites have undergone several changes over the years, due to the advancements in cement production processes resulting in higher-grade cements and the advent of modern pozzolanic and chemical admixtures, leading to strengths reaching the levels of steel in compression, while having significantly improved performance characteristics even in the most aggressive of environments. However, being a highly complex composite with so many materials of varying sizes, shapes, and textures, the prediction of the strength and performance of the resultant material has always been a matter of serious concern, without stringent control on the constituents. The large and ever expanding database of research findings with several different local constituents, be it aggregates or the cements produced or the admixtures utilized in these concrete composites, also causes a certain amount of confusion in understanding the material.

In the context of the normally vibrated concretes, be it the general-purpose concretes, high-strength concretes, no slump concretes, or even lightweight concretes, recommendations are available for arriving at a concrete of a specific strength and consistency required for a particular application in the construction activity. In brief, the methodology adopted was to define the water–cement ratio in terms of the strength required for the structural member. Depending on parameters such as the construction practice, member size, and dimensions, the consistency or the workability of concrete was fixed. The workability ranges from no slump to a collapse slump based on the compaction procedures adopted. Depending on the constituent materials, particularly the maximum size of the aggregate, the water content is defined for that workability. After this the coarse aggregate and fine aggregate proportions are fixed or a continuously graded aggregate is recommended for each maximum size of the aggregate. All these were possible through an understanding of the gradation of aggregates and the amount

of paste and mortar contents including water, which were all chosen from a very large database of the experimental evaluations and field experiences that are available on these types of normally vibrated concrete systems. One important factor that was also learned during these investigations was that an inadequate compaction of the resulting mass can significantly affect the strength of the composite ultimately. Several compaction procedures such as vibro-compaction, high-frequency vibration, vacuum dewatering, spinning, and pressure application have all been used effectively, depending upon the member details and construction practices available. Naturally, the emphasis is more on appropriate concrete compaction methodologies to alleviate the problems associated with the lowering of strengths during these processes. Though the most desired parameter in defining the characteristics of concrete is strength, which is related to the water to cement ratio, the fact that it can be produced with various workabilities at different water contents was also well established. Slump is a measure of the workability, and structural concretes with no slump to collapse slump characteristics can be produced in practice with water contents ranging from 150 to 215 kg/m³, as recommended in the ACI guidelines (ACI 211.1, 1997).

In this complex scenario wherein the concrete has undergone several significant modifications to cater to the varying needs of the construction industry, the modification that has attracted the attention of the industry in recent times is the concept of self-compacting or self-consolidating concrete (SCC), a concrete that consolidates under its own weight. This concept of SCC, originally articulated by Okamura (1995), came into existence in an effort to design a concrete mix that could consolidate and fill without any difficulty the massive end anchorages of the Akashi-Kaikyo bridge with its highly impenetrable surface reinforcement cage and anchorage details. These SCCs have also been referred to in the literature as SCCs, self-placing concretes, and self-levelling concretes by a few, depending upon the requirements and perception. Semioli (2001) opines that a less dramatic terminology such as self-accommodating concrete might be more appropriate to describe the self-levelling and self-compacting properties that permit easier installation and working at sites for Lafarge's "Agilia," which was termed a self-placing concrete by them. He also discussed its use for both horizontal and vertical applications as well as in the repair and rehabilitation of an old courthouse structure. Szecsy (2002) presented a broad discussion on the nomenclature as well as the technology. He opines that each of these different names defines a specific aspect of the type of concrete, namely, SCC—a concrete that consolidates through gravity to achieve maximum density without the need for vibration, self-levelling concrete (SLC)—a concrete that can seek a level grade within the formwork, and self-placing concrete (SPC)—a concrete that has ease of placement and has the ability to be both self-compacting and self-levelling. The various admixtures that help in achieving self-compactability (mostly polycarboxylate-based superplasticizers in recent years) and a few tests that establish the different workability characteristics have also been presented. Also, others followed

a similar approach in defining what is expected of SCC over the years. To be more specific the name carries the entire meaning of the expectation from the cementitious composites developed.

1.2 Historical Development

One of the significant developments in the area of concrete technology could be traced to the advent of superplasticizers, though certain classes of plasticizers have always been available from times immemorial, even from the early lime concrete technology periods. This change is essentially because concretes with even a limited slump of just 25–50 mm could be readily reduced to a fluid consistency with collapse slump, if only it is ensured that there is enough sand and fines (even cement as in the case of high-strength concretes of lower water–cement ratio) in the mix. The simple yet often forgotten rule in the development of these concretes was to increase the sand content by about 10% and also to have a good gradation in the coarse aggregate fractions. These are then termed as superplasticized concretes; while the same superplasticizers could be utilized in concretes where the slump was nearly retained at the original level of 25–50 mm by appropriately reducing the water content (almost by about 20% if possible) and be termed as high-range water reducing admixtures, resulting in significantly higher strengths in these concretes. This in a way promoted the initial development of high-strength concretes, which were presumed, even if wrongly, to be an approach for realizing high-performance concretes due to their lower water–cement ratio and the resultant discontinuous capillary pore structure that could inhibit the permeation of moisture and environment.

The second significant development in concrete technology is the introduction of silica fume (an industrial waste from the ferrosilicon industry) as a pozzolan and the consequent development of very high-strength high-performance concretes. Simultaneously a lot of interest was generated in the use of secondary cementitious materials or mineral admixtures, which not only ensure a saving of cement and economy but also impart a higher performance. The need for an effective utilization of the abundantly available industrial wastes like fly ash from thermal power stations as an industrial waste and slag from steel plants (in the form of ground granulated blast furnace slag, GGBS) also contributed to the formulation of binary cement composites. These pozzolans in conjunction with the available superplasticizers paved the way for an entirely new regime of concrete and concrete composites that proved to be of a significantly higher performance with the possibility of also achieving very high strengths. Many other materials such as metakaolin, zeolite, and rice husk ash (RHA) have also come to be used as pozzolanic materials.

SCCs have essentially evolved in the background of these significant changes that took place in the past few decades. Okamura published a few studies prior to his proposed mix design methodology for SCCs leading to its use in the end anchorages of the Akashi-Kaikyo bridge (Okamura, 1994, 1995, 2003). The method, simply stated, attempted to achieve a highly workable and thixotropic mix through augmented fines and superplasticizers while reducing the coarse aggregate content. After this initial semi-empirical approach of modifying the conventional concrete design, researchers appear to have looked for avenues to achieve self-compactability through several different approaches, which are later, delineated. It looks obvious that the primary objective of any design methodology proposed to date is to achieve a cohesive and stable SCC without much thought given to its strength or performance characteristics.

A closer look at the broad spectrum of concrete composites will clearly show that SCCs, considered to be new in the present day context, are not in any way totally unknown to the industry. Several references could be found to concretes of collapse slump, sometimes termed as flowing concretes, self-levelling concretes, and grouts that exhibit slumps of 200–250 mm and even beyond, which were formulated to have no bleeding and segregation either through manipulations in cement content or by using thixotropy-imparting agents like vinyl- or cellulose-based materials. These were far more common as concrete composites suitable for underwater application with the necessary anti-washout characteristics even in the continuous or oscillatory flow regimes occurring in river, estuarine, or ocean environments (Gerwick, 2015). Some such precursors to SCCs have been described by Collepardi (2001, 2005, 2007). Apart from these facts, spatiality grouts of self-levelling nature have been in the market for quite some time now, and in applications requiring higher thickness of concrete for repair and rehabilitation these have been used incorporating 50%–60% well-graded coarse aggregate of a maximum size up to 10–12 mm. Such concretes were also developed in the laboratory for applications such as jacketing repairs of corroded columns and beams in both industrial and marine structures.

Some other aspects that are often quoted as factors that distinguish an SCC from a normally vibrated concrete (NVC) are the use of fly ash (maybe up to about 30%–40% of the total cementitious material or sometimes other fine materials as powder extenders) and a viscosity modifying agent (VMA). However, concretes with supplementary cementitious materials like fly ash, particularly to ensure reasonable economy in the normal strength concrete production, are well known. It is also known that to control the increased wetting water requirements of the increased surface area due to the presence of these powder extenders superplasticizers are often the only solution unless the total cementitious materials are kept well within the limits. This aspect of the need for superplasticizers becomes obvious in the case of superfine or nano pozzolans like silica fume, nanosilica, and calcined clays.

Several research reports are already available in the literature presenting concrete composites of very high workability, even with flowing characteristics, with many of these superfine high-end pozzolans. It is also to be noted that the design of these concretes was based on the presently available mix design methodologies of normally vibrated concretes, with only minor adjustments, essentially to the water and superplasticizer requirements wherever necessary. It is probably appropriate to point out at this particular stage that several publications have also taken into account the cementitious strength efficiency of these pozzolans, to design with confidence concretes of the desired strength and performance.

Having looked at all these perspectives one wonders if there is any special concrete composite that needs to be presented under the name of SCC. Extending a little further into what is known, it is obvious that even if we were to term a group of concretes in a special class called SCCs, one cannot be far wrong in saying that these can be designed with the available knowledge and the proposed methodologies for normally vibrated concretes. The later part of this book deals with some of these aspects and also delineates a methodology based on the existing concrete mixed design procedures to ensure a perfectly satisfactory SCC.

1.3 Definition

Self-compacting concrete, as the name indicates, is one that has the property of self-consolidating, self-placing, or self-levelling as indicated by several of the alternative names it has in the literature. However, some of the national bodies felt it is prudent to define it as a concrete that conforms to certain qualities, essentially to set it apart from the traditionally vibrated concretes, which in themselves will never come under one single group as can be seen by referring to them as normal concrete, heavyweight concrete, lightweight concrete, high-strength concrete, and even no slump concrete just to name a few. Some of these definitions are presented here to give a clear picture of the perceptions of each of these national bodies.

The Japanese recommendations (1999) define SCCs as concretes with self-compactability, which is defined in the Japanese recommendations as “the capability of concrete related to the placeability of concrete, with which it can be uniformly filled and compacted in every corner of the formwork by its own weight without vibration during placing.” This definition essentially talks about its filling ability, though the terms deformability, passability, placeability, and segregation are also defined in the text of the report.

The European guidelines for SCCs (2005) recognize this as “the concrete that is able to flow and consolidate under its own weight, completely fill the

formwork even in the presence of dense reinforcement, whilst maintaining homogeneity and without the need for any additional compaction.” It obviously recognizes filling and passing ability, apart from segregation resistance, as the essential characteristics.

Probably a fairly inclusive definition of SCC is presented by the ACI (2007), which states that “Self-consolidating concrete (SCC) is highly flowable, non-segregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation.” It also states that, in general, SCC is concrete made with conventional concrete materials and, in some cases, with a VMA. Apart from all other factors recognized in the earlier definitions, this recognizes the importance of the encapsulation of reinforcement, which is an essential prerequisite for the structural performance of reinforced concrete constructions.

As already stated, the primary aim in each of these definitions, as well as every effort of the research and developmental activities related to SCCs, appears to center around the aspect of self-compactability without giving credence to the fact that this could only be a further extension to the already existing concrete composites at the various consistency levels as defined in the various codes. The fact that it occupies the entire void space in a formwork appears to be reason enough for it to be referred to as a concrete of high performance though this alone is not adequate in practice. Apart from this, if it contains a pozzolanic material like fly ash even just at about 30% as recommended in most research efforts, one can comfortably consider this to be a concrete of higher performance compared to the concretes without such a pozzolanic replacement using other simple forms of powder extenders that may not help in ensuring such a high performance.

It may not be out of place to have a look at the characteristics that are essential to term a particular concrete as a self-compacting or a SCC—a concrete with the high workability required to flow through densely reinforced structural elements under its own weight and adequately fill voids without segregation or excessive bleeding and without the need for vibration to consolidate it. These characteristics are basically recognized by the Precast/Prestressed Concrete Institute (2003):

Filling ability (flowability)—ability to flow and fill under its own weight all spaces within an intricate formwork, containing obstacles, such as reinforcement.

Passing ability—ability to flow through openings between reinforcement approaching the maximum size of the coarse aggregate without segregation or blocking, and

Stability (segregation resistance)—ability to remain homogeneous during transport, placing, finishing and also through the initial phase of hardening.

1.4 Formulations and Classifications of SCCs

The available procedures for the proportioning of self-consolidating or SCCs could be categorized broadly into three main types. The first is the powder type—essentially increasing the powder content while reducing the water to power ratio to ensure that the aggregates are supported in such a viscous medium of paste and mortar. Alternatively, it was felt that it was possible to generate a similar effect by adding a VMA to provide the same segregation resistance to a concrete of high fluidity. Lastly, a combination of both these methodologies could be used to ensure an optimal utilization of the effects of both.

In every one of these formulations the use of additional powder material content is almost always taken for granted. In the first place the increased powder content can be achieved in two ways either by increasing the cement content, which is highly uneconomical and has its own limits even if one were to consider the increase in strength appropriately, or this can be achieved by using waste powders like stone dust to do the needful. A simple alternative that is presently available is to realize this increase through low-cost, ubiquitously available industrial waste by-products like fly ash and GGBS, which will also perform as low-end secondary cementitious materials. Some researchers also suggest the use of limestone powder readily available in the cement plants as inert filler, though the limestone powder was also observed to be exhibiting some chemical reactivity. Apart from these materials there are several other high-end pozzolanic materials like silica fume, metakaolin, rice husk ash, calcined clays, and so on, which can also be used for this purpose more effectively producing high-strength concretes.

Another important aspect is the fact that while most research reports in general try to classify the concrete as self-compacting once the slump flow is above 500 mm, there are three different slump flow regimes or ranks defined in the various national recommendations. These were also classified into subgroups of SCC based on other characteristics like viscosity or passing ability. SCCs are classified into three different categories or class ranges by JSCE (1999), essentially based on their slump flow characteristics (650–750; 600–700; 500–650 mm as Ranks R1, R2, and R3), basically to suit the needs of the construction conditions, like the minimum gap between reinforcement and the amount of reinforcement to cater to the filling ability needs of the concrete required. Similar classifications based on the parameter of interest are also available in other national specifications like the European and the American. It is in fact said that the choice of the specific characteristic and the subclass or regime of SCC that needs to be adopted essentially stems from the requirements in the field, like the dimensions and intricacy of the structural member, thickness, density of reinforcement, and so on. This in fact is very similar to that for traditionally vibrated concretes, which can be produced with various workabilities or slump, a measure of the workability. Most of the design procedures reported for producing SCCs have concentrated on

proportioning of the mix constituents to achieve the primary requirement of self-compactability, but have not focused on a procedure to design concrete of a desired strength and workability that characterizes the design of conventional concretes with or without the chemical and mineral admixtures, not to mention the durability aspects.

Having considered all these perspectives, one wonders if there are any special concrete composites that need to be presented under the name of SCCs. Extending a little further into what is known, it is obvious that even if we were to term a group of concretes a special class called self-compacting or SCCs, one cannot be wrong in saying that these can be designed with the available knowledge and the proposed methodologies for normally vibrated concretes. The later part of this book deals with some of these aspects and also delineates a methodology based on existing concrete mixed design procedures to ensure a perfectly satisfactory SCC.

One important aspect that is worth mentioning at this stage is that this study was realized in such a way to ensure that the information collated and the databanks established are comprehensive and are representative of the overall picture and yet they are separated to ensure an appropriate recognition of the intrinsic chemical dynamics of the cementitious systems analyzed. This is to ensure true and representative relationships between the appropriate parameters. The parameters have all been chosen in such a way that they are the most acceptable to date and were seen to have an unequivocal validity in the other systems of cementitious materials that were investigated over the years. Needless to say that the approach is not purely mathematical or empirical as could happen in a case where it is purely governed by the numerical system being analyzed through totally fuzzy or neural logic methods without connecting them to the physical and chemical aspects of the system in question, which could lead to serious misinterpretations. In fact both the spectral width of the data and also the parameters of investigation have always been tempered by an overall understanding of not just the material science and technology of concrete, but also an understanding of its requirement as structural material and its performance in the environment in which these structures are expected to perform. In addition, the possibility of representing not just the concepts but also the outcomes in them in a ready to use format for the practitioner was also attempted wherever possible.

1.5 Potential and Limitations

In the present scenario, SCCs can be treated as essentially a newer group of concretes that do not require any compaction energy through vibration or other means. However, as the emphasis is on self-compactability, the more important and defining structural requirements of strength and performance

have not attracted adequate attention. Naturally, the resulting SCCs, unless appropriately addressed otherwise, may not comply with any specific strength or performance class as required in the structural practice. The discussions in the preceding part of this chapter clearly bring out the fact that SCCs of various strength grades can be appropriately designed if one has better understanding of the specific relations as in the case of traditionally vibrated concretes.

At this stage probably the most important requirement, to fully understand and realize the complete potential of SCCs, is to look at the total picture through a proper appreciation of the concretes reported so far in the literature and arrive at acceptable guidelines and recommendations, not just to arrive at an SCC with the required self-compactability but to be able to design it with an appropriate confidence having the required flowability and also resulting in a concrete of a specific strength and performance grade for a specific structural application. In fact many design efforts essentially started with a very similar objective of obtaining a concrete of a particular strength grade, but the experimental investigations by their own admission have resulted in concretes of different strength grades. Also, the performance characteristics reported, if at all, have not been related to the constituent material characteristics and quantities to ensure an appropriate understanding and adoption. In a few cases, the mechanical characteristics like the tensile strength and modulus are related to the strength, which were observed to be nearly following the accepted relationships used for normally vibrated concretes. This in a way was the justification for an approval of the use of SCCs in structural concrete applications. Even so there are a few who consciously advocated caution in adopting SCCs without an appropriate verification. Some specific aspects like early age characteristics, strength development, shrinkage, bond with reinforcement, and creep, relaxation, and anchorage stress distributions particularly for prestressing applications need a better understanding. There is an urgent need to address some of these aspects at least on a case-to-case basis to ensure safety of the structural systems or alternatively suggest ameliorative measures that could address these concerns based on an appropriate background in such cases from previous experience. It is these important yet fundamental concerns that instigated and initiated the present study to look at the entire spectrum from a structural engineering application standpoint. At the same time appreciating the material science characteristics that are required to ensure an appropriate system of SCCs for practical applications in all the relevant flow regimes is also needed.

1.6 Future Prospects

This concept of SCC, originally articulated by Okamura (1994), was seen to be mainly to harness its advantages such as the elimination of vibration and decreasing time and labor costs along with a reduction in noise pollution

during compaction. It is presumed that it could ensure better durability due to compaction effectiveness and the additional fines that generally are of a pozzolanic nature. The basic difference of SCCs from conventional concretes is in ensuring the three main attributes of filling, passing, and segregation of these concretes through modifications in the proportioning of the constituents, like increasing the fines or by the addition of a VMA that imparts the required segregation resistance.

Most design procedures for SCCs have concentrated on proportioning of the mix constituents to achieve the primary requirement of self-compactability, but have not focused on a procedure to design the concrete of a desired strength and workability that characterizes the design of conventional concretes with or without chemical and mineral admixtures, not to mention aspects of durability. This study is an attempt to discuss the various parameters that influence the making of SCCs and to propose a few simple and effective guidelines to arrive at the same with specific strength and durability characteristics.

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