Flexural response of reinforced concrete beams using various cementitious materials

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University of Toledo
A Dissertation
entitled

Flexural Response of Reinforced Concrete Beams
Using Various Cementitious Materials

by

Vijaya Sena Reddy Karnati

Submitted to the Graduate Faculty as partial fulfillment of the requirements for the
Master of Science Degree in Civil Engineering

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College of Graduate Studies

The University of Toledo
August 2016
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The present study explores the effect of fly ash, recycled aggregate concrete (RAC),
ultra-high strength concrete (UHSC) and self-compacting concrete (SCC) on the per-
formance of reinforced concrete beams. The nonlinear finite element analysis using
ANSYS software program was employed to model RC beams. A smeared crack ap-
proach was used for the concrete in all finite element models. The compressive and
tensile strengths, modulus of elasticity, and poisson’s ratio for various cementitious
materials required in the finite element analysis modeling were collected from the
literature. Two different beams were considered; first beam made with the normal
strength reinforced concrete and; second beam made with high strength SCC, were
validated and compared to experimental results of an existing study in the literature.
The first validated RC beam was investigated for flexural response of concrete beams
made with mixtures of 25% fly ash, ultra-high strength concrete, 50 and 100% re-
cycled concrete aggregates, and normal strength self-compacting concrete. For the
second validated high strength SCC beam, the effects of silica nano powder and silica
fumes were also studied.

The results obtained from developed models of RC beam finite element analysis
were compared to the experimental results and they were in good agreement. From
parametric studies on the first validated beam, concrete mixtures of 25% fly ash and
50 and 100% recycled concrete aggregates, and normal strength self-compacting concrete could provide similar ultimate load and displacement capacities as the control beam. However, the RC beam with ultra-high strength concrete showed a higher gain in load capacity and lower displacement was observed at the mid-span due to additional stiffness. For the second validated high strength SCC beam, under approximately the same ultimate load level, the deflection at mid-span was lowest when silica nano powder and silica fumes were combined. The findings contribute to provide researchers with necessary information that influence the design of RC beams using waste materials or by-products in concrete as well as high strength concrete mixtures.
I dedicate this thesis to my family, especially my grandmother, Urmila Kuppireddy and my grandfather Penta Reddy Kuppireddy for giving me love and support in each step of my life; and my brother Jayasimha Reddy Karnati for his unconditional love and support.
Acknowledgments

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List of Abbreviations

ACI .................... American Concrete Institute
ASTM .................... American Society for Testing and Materials
AASHTO ................. American Association of state highway transportation
BISO ..................... Bi-linear Isotropic Hardening Model
FEA ...................... Finite Element Analysis
FEM ...................... Finite Element Methods
FEA ...................... Finite Element Analysis
LVDT .................... Linear Voltage Displacement Transducers
RC ....................... Reinforced Concrete
RCA ...................... Recycled Concrete Aggregate
UHSC ..................... Ultra High Strength Concrete
SCC ...................... Self Compacting Concrete
W/C ...................... Water Cement ratio
# List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>$\sigma$</td>
<td>Stress</td>
</tr>
<tr>
<td>$\beta_t$</td>
<td>Shear Transfer Coefficient</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Deflection</td>
</tr>
<tr>
<td>$\beta_0$</td>
<td>Open Crack</td>
</tr>
<tr>
<td>$\beta_C$</td>
<td>closed Crack</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Diameter</td>
</tr>
<tr>
<td>I</td>
<td>Inertia</td>
</tr>
<tr>
<td>M</td>
<td>Moment of Curvature</td>
</tr>
<tr>
<td>$v$</td>
<td>Poisson’s ratio</td>
</tr>
<tr>
<td>$E_C$</td>
<td>Modulus of elasticity of concrete</td>
</tr>
<tr>
<td>$E_s$</td>
<td>Modulus of elasticity of Steel</td>
</tr>
<tr>
<td>$E'_s$</td>
<td>Tangential Modulus of elasticity of Steel</td>
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<tr>
<td>$f'_C$</td>
<td>28-days concrete compressive strength of concrete</td>
</tr>
<tr>
<td>$f'_t$</td>
<td>Splitting Tensile strength of concrete</td>
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Chapter 1

Introduction

1.1 General

Despite advances in technology and construction techniques for building structures the use of cement-based materials is believed to improve the sustainability of concrete mixtures. In general, the concrete material is a mixture of cement, sand, water and aggregates. However, if the concrete materials used in this construction practices are not controlled, it would result in impacting the environment negatively and less durable building structures. Our major concern is about the negative global warming, reduction in amount of water usage and workability.

In recent years, different cement-like materials, such as concrete with fly ash, recycled concrete aggregates, ultra-high strength concrete and self-compacting concrete with different binder contents having silica and nano silica fumes, have gained significant importance due to their advantages in reducing negative impact on the environment, as well as their availability and mechanical properties. In the following sections different types and characteristics of these cementitious materials are described.
1.2 Construction Material Types and Characteristics

1.2.1 Fly Ash

Fly ash is a by-product of coal power stations generated by combustion of coal. It is mainly a mixture of oxides of calcium, iron, silica, alumina, magnesium and many other substances. They are in a phase of glassy nature due to their production in higher temperatures. In the USA fly ash is usually produced in coal-fired power plants, but nowadays about 43% of fly ash has been recycled and used in the production of concrete with partial replacement of portland cement. According to Resource Conservation and Recovery Act (RCRA), coal fly ash is classified as unhazardous waste material. According to ASTM C618-15, there are two types of fly ash as follows:

- Class C fly ash where sub-bituminous coals or lignite are used in the production of this type.
- Class F fly ash which is known as low calcium fly ash obtained from bituminous coals.

1.2.2 Ultra-high Strength Concrete

For the benefits of the construction industry, there have been many materials developed. In this process, ultra-high strength concrete (UHSC), also known as reactive powder concrete which is composed of composite materials having higher compressive strengths, has been developed in the early 1990s. UHSC comprises of very fine powders of cement materials and super plasticizer. The following are the advantages of using UHSC:
• Higher durability,
• Improving resilience,
• Compatible with pre-stressed structures,
• Higher compressive and tensile strengths.

1.2.3 Recycled Concrete Aggregates

The use of recycled concrete aggregates in concrete structures has become a common practice for many years. In the U.S.A alone 140 million tons of concrete are recycled each year (ReCrete Materials, Inc., 2008). Advantages of using a recycled concrete aggregate mix design are:

• Optimized plastic shrinkage and initial set times,
• Improved finishibility,
• waste aggregates to usable concrete aggregates,
• Lower material cost,
• Maintaining the product quality,
• Reduced negative impact on environment.

1.2.4 Self Compacting Concrete

The concept of self-compacting concrete is to produce concrete without the need for full compaction as proposed by professor Okamura (2003). The SCC materials have the capability of being placed anywhere without segregation, uniformity in structural outline, proper filling, bond strength improvement and faster constructability. A Self-compacting concrete prototype was first developed by Ozawa and Maekawa
at the University of Tokyo, Japan, in collaboration with leading concrete contractors during late 1980s (RILEM TC 174 SCC, 2000). SCC material components have the ability to be easily placed into form works on their own weight without any voids, thus ensuring proper filling. The advantages of SCC are as follows:

- Faster construction periods,
- Reduced labor costs,
- Higher flowability,
- Improved finishability,
- Maintaining the product quality,
- Higher strength and increased ductility.

Nowadays, the use of SCC in construction has become popular due to its practical applications and the standard design codes and requirements of SCC in constructions have been developed by the American Concrete Institute (ACI 347R) manual of concrete practice, the American Society for Testing and Materials (ASTM), Centre for Advanced Cement-Based Materials (ACBM) and National Ready Mixed Concrete Association (NRMCA, 2004) to name a few.

### 1.3 Objective and Methodology of the Thesis

The main objective of this research is to study the effect of substituting normal concrete with different properties and characteristics of cementitious materials such as recycling concrete aggregate (RCA), fly ash, ultra-high strength concrete (UHSC) and self-compacting concrete (SCC) incorporated in building structures.
In particular, to have a better understanding of beams behavior for cracking stresses, crushing stresses, shear transfer coefficients, ultimate loads, load versus mid-span deflection are discussed in detail. The methodology used for current research are as follows:

- Extensive literature was done to understand the properties of different cementitious materials from previous articles and experiments is presented in chapter two.

- The numerical simulations and modeling techniques for design of different concrete materials were performed using version 14.5 ANSYS computer software program. The usage of ANSYS in FEA modeling has been increased due to advantages in designing very reliable, efficient and enhancing structural capabilities.

- The behavior of normal reinforced concrete in flexure is calibrated with the experimental data using ANSYS.

- The flexural behavior of normal strength reinforced concrete beam is compared with counterpart beams made with substituted concrete types using Finite Element Analysis (FEA).

- Parametric analyses on high strength self-compacting concrete beam have been studied for its behavior in flexure.

- To validate normal beam concept for application of high strength concrete structures behavior and effects of silica nano powder and silica fumes on the flexural behavior of high strength self-compacting concrete beam were also analyzed.

- Ultimate strains and stresses of different materials were examined. Investigation on different material parameters and application of different cement materials to control model for calibration.
• FEA analysis and simulations were performed to analyze their cracking load’s patterns and flexural behavior of beams using ANSYS software program.

This research study is intended to understand the addition of different properties of the supplementary cementitious material in normal concrete structure to improve the working environment conditions and productivity using ANSYS computer software program. The simulations were performed based on compressive, splitting tensile strength, flexural strengths and few other parameters obtained from previous works. The previous studies have been utilized to analyze the results and which are similar to real life responses.

1.4 Thesis Outline

This thesis dissertation consists of five chapters and structured as follows:

In chapter one, introduction my thesis topic and a brief review of different types and characteristics of cementitious materials have been discussed.

Next in chapter two, the literature review is done on properties, characteristics, constituents, compressive strengths, tensile strengths and mix designs of different types of cementitious materials. The review on the effect of silica nano powder and silica fume on the strength of high strength self-compacting concrete was reviewed in detail.

Next in chapter three, the detailed view on experimental model from previous work on reinforced normal concrete beam is presented and validated. The flexural behavior of validated beam with incorporation of different supplementary cementitious materials properties are analyzed and compared.

Next in chapter four, the detailed view on an experimental model from previous work on reinforced high strength self-compacting concrete beam is presented and calibrated with the validated model. The flexural behavior of the validated beam
with the effect of silica properties is analyzed and compared.

Next in chapter five, conclusions drawn from the research studies are presented and furthermore scope for future research is recommended.
Chapter 2

Literature review

2.1 Introduction

In this chapter, we discuss the literature review on reinforced concrete, fly ash concrete, ultra-high strength concrete, recycled concrete aggregates and self compacting concrete materials. In the past, attempts were made to study various cement materials and their mechanical properties. The following is a literature review, performed on parametric and non-parametric studies to analyze the behavior of different cementitious material properties, such as compressive strengths, the effect of plasticizers, tensile strengths, flexural strengths and ductility from various published articles.

2.2 Reinforced Concrete

This section discusses a comprehensive work published in the area of RC beam to provide detailed understandings. Many experiments were conducted to study the flexural behavior of reinforced concrete beams.

Kachlavev (2001) has simulated finite element models of RC beams in order to observe the linear and non-linear responses up to a load of failure. He also studied about the results of three other beams with 3-dimensinal layered elements using the ANSYS finite element program. The beams analyzed are as follows:
- Control beam with CFRP plates
- Control beam with GFRP plates
- Control beam with CFRP and GFRP plates.

He validated one-quarter of beam due to symmetry using the interface. To model concrete and reinforcement using solid65, link8 elements and steel cushion at loading points, concrete volume was meshed properly using necessary mesh attributes. Individual elements were modeled with the nodes created by concrete mesh for reinforcement. Normally, the mesh is created by trial process to achieve proper density. Smeared crack approach was used to model all the elements. Stirrups were also modeled using link8 elements. The results were compared with the results provided by experimental beams by Buckhouse (1997). The observations made from the results were load strain plots at any point in the beams, mid-span load-deflection plots and all levels of cracking and their patterns. He also observed that slight changes in youngs modulus and compressive strength made a huge difference in validation.

Riveros and Gopalaratnam (2013) studied the fracture response of RC deep beams and also investigated on the strength and size of beams. Riveros and Gopalaratnam studied the various parameters, like crack initiation to sizes of beams, deflection capacities due to changes in sizes, failure mechanisms due to shear span to depth ratios, brittle natures of beams, compression and tension softening of concrete beams, bond slip behavior between concrete and reinforcement, and yielding longitudinal reinforcement. The development also incorporates the Delaunay refinement algorithm to create a triangular topology which is then transformed into a quadrilateral mesh by the quad-morphing algorithm. These two techniques allow automatic re-meshing using the discrete crack approach. Nonlinear fracture mechanics is incorporated using the fictitious crack model and the principal tensile strength for crack initiation and propagation.
Kasat and Varghese (2012), in the design of efficient structures, has studied prestressed concrete beams using ANSYS for finite element analysis under transverse loading conditions, which was an economical way and obtained solutions as natural structures. He obtained the failure load similar to the experimental results and also hand-calculated stresses, initial cracks occurrence and deflections of beam at any point.

Table 2.1: Stress calculations (Kasat and Varghese (2012))

<table>
<thead>
<tr>
<th>Method of analysis</th>
<th>Stresses in top fiber (N/mm)</th>
<th>Stresses in bottom fiber (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>calculation</td>
<td>-11.6</td>
<td>1.16</td>
</tr>
<tr>
<td>ANSYS</td>
<td>-10.48</td>
<td>1.16</td>
</tr>
</tbody>
</table>

They found that failure mechanism, cracks, deflections, stresses and progressing cracks were modeled accurately using FEA and results obtained were very close to the hand calculations.

Vasudevan and Kothandaraman (2012) have studied the RC beams under two point loading conditions. They used ANSYS 12.0 for finite element study of the beam with the smeared crack approach. Loads at initial cracks and ultimate load capacities were analyzed according to the IS 456:2000 code. They analyzed the batch mode approach and graphical user interface advantages. In their work, they simulated the entire processing of model for FEA analysis by creating a single batch file before modeling in ANSYS APDL version. ANSYS was used for plotting of load vs deflection curves, crack propagation and steel yielding based on material properties. They observed results obtained from FEA, which was very close to the results of experimental findings.

Saifullah et.al (2011) have studied the nonlinear analysis of RC beam for different shear reinforcement patterns by FEA analysis. They have selected RC beams with and without different shear reinforcements using ANSYS for simulations. In
this study, the cracks occurrence in the concrete model and failure of concrete with different types of cracks were studied. When the compressive crushing strength of concrete and modulus of rupture of concrete became less than the stresses occurring on them, it resulted in propagation of cracks in concrete. These cracking and crushing parameters are accounted for failure criteria for concrete model. ANSYS also considers other two parameters i.e. uniaxial tensile and compressive strength for failure of concrete. They compared their works with Wolansoki (2004) results which were in good agreement with each other. Finally, they found different parameters like crack formations, effective shear reinforcement pattern model.

Mohamad Najim (2007) studied the nonlinear analysis of RC beams under pure torsion. The torsional strength due to the changes in the length of beam and cracks propagation due to various loading conditions were studied and analyzed. He has tested six beams with different length and same reinforcement ratios as per the ACI318-05 code. The author considered multilinear isotropic stress-strain curve for the concrete model from the equation by Mac Gregor (1992) and modeled steel bars and loading plates using bilinear kinematics hardening (BKin). Torque-twist angle for the beams was analyzed with incremental torque with application of uniform load and convergence of solution stopped at the reach of ultimate load. Here ductility of the beams was analyzed during post cracking stages, prediction of elastic torque, cracking torque, ultimate torque and stresses in reinforcements were observed.

### 2.3 Fly Ash

In this section, we discuss various researchers work done on the topic of fly ash and beam with fly ash to provide a detailed literature review. Many experiments were conducted to study the response and behavior of fly ash in concrete beams.
Feng and Clark (2011) have studied the fly ash products based on the standard physical and chemical requirements of ASTM C 618 in order to improve the usage of fly ash in Portland cement concrete. They have tested forty-nine fly ashes from different locations in U.S and used Portland cement according to ASTM C 311 standards. The compositions of Portland cement and fly ash shown in Table 2.2. They observed that addition of fly ash to cement paste had a good influence on properties as well as workability of concrete.

Table 2.2: Chemical composition of Fly Ash (Feng and Clark (2011))

<table>
<thead>
<tr>
<th>ID</th>
<th>Portland cement % by mass</th>
<th>Fly ash % by mass</th>
</tr>
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<tbody>
<tr>
<td>CaO</td>
<td>64.1</td>
<td>0.37- 27.68</td>
</tr>
<tr>
<td>SiO</td>
<td>20.13</td>
<td>27.88 59.40</td>
</tr>
<tr>
<td>AlO</td>
<td>5.78</td>
<td>5.23 33.99</td>
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<tr>
<td>FeO</td>
<td>2.35</td>
<td>1.21 - 29.63</td>
</tr>
<tr>
<td>MgO</td>
<td>1.19</td>
<td>0.42 - 8.79</td>
</tr>
<tr>
<td>SO</td>
<td>3.53</td>
<td>0.04 - 4.71</td>
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<td>NaO</td>
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<td>0.20 - 6.90</td>
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<tr>
<td>KO</td>
<td>0.77</td>
<td>0.64 6.68</td>
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<td>TiO</td>
<td>0.37</td>
<td>0.24 1.73</td>
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<tr>
<td>LOI</td>
<td>1.63</td>
<td>0.21 28.37</td>
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</tbody>
</table>

A.A. Ramezanianpour and V.M Malhotra have studied the compressive strength and porosity of fly ash in cement mortar. They have investigated low calcium fly ash (ASTM class F) to have the following properties:

Concrete mixtures were proportionated according to design mix where water to cement ratio was kept constant as 0.5:1 and density of fly ash used were 92 Kg/m³. They cast six cylinders of size 102*203 mm using four different curing process as follows: The observations from fly ash concrete cured with standard moist curing conditions has shown higher strength, less porosity and more resistance to chloride ions penetrations, but poor performance was exhibited by specimens which did not receive curing, whereas curing at 38 °C relative humidity (RH) has shown equivalent properties at initial stages but not at later stages.
Table 2.3: Physical properties of Fly ash (A.A. Ramezanianpour and V.M Malhotra (1995))

<table>
<thead>
<tr>
<th>Description of test</th>
<th>Fly ash ASTM class F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>2.68</td>
</tr>
<tr>
<td>Fineness- passing 451 (%)</td>
<td>81.7</td>
</tr>
<tr>
<td>Surface area Blaine (m² /Kg)</td>
<td>306</td>
</tr>
<tr>
<td>Silicon dioxide</td>
<td>40.9</td>
</tr>
<tr>
<td>Aluminium dioxide</td>
<td>18.6</td>
</tr>
<tr>
<td>Ferric oxide</td>
<td>28.9</td>
</tr>
<tr>
<td>Calcium oxide</td>
<td>1.87</td>
</tr>
<tr>
<td>Magnesium oxide</td>
<td>1.01</td>
</tr>
</tbody>
</table>

Table 2.4: Curing Methods (A.A. Ramezanianpour and V.M Malhotra (1995))

<table>
<thead>
<tr>
<th>No.</th>
<th>Curing regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Standard moist curing following demoulding</td>
</tr>
<tr>
<td>2</td>
<td>Curing at room temperature after demoulding</td>
</tr>
<tr>
<td>3</td>
<td>Curing at room temperature after two days of moist curing</td>
</tr>
<tr>
<td>4</td>
<td>Curing at 38°C and 65% RH</td>
</tr>
</tbody>
</table>

Naganathan and Linda (2013) have studied the effect of grounded fly-ash with a mortar and different levels of percentages of fly ash were replaced with cement mortar cubes. All mixed design cubes were tested for strength and water absorption.

They have noticed that strength of fly ash cubes at early ages was decreased and increased as their ages progressed. And also their durability decreased with increase of fly ash fineness quantity. The addition of finely grounded fly ash from the source to cement mortar has improved the strength, reliability, and pozzolanic-activity with timely curing.

### 2.4 Ultra high strength concrete

In this section discussions on various researchers work done on topic of ultra-high strength concrete material and application of material on RC beam to provide
detailed literature review. Many experiments were conducted to study the behavior and flexural response of UHS concrete beams.

According to Caijun et.al (2015), UHPC refers to Concrete materials with admixtures or super plasticizer resulting in compressive strength higher than 150 MPa. They have studied about the basic principles for UHPC design and materials needed for preparation. The density of UHPC is very high which is due to close packing of solid particles, hydration reaction in cementitious materials and improvement in the interfacial transition zone. The cementitious material has a variety of admixtures as following Portland cement, silica fume, granulated blast furnace slag, fly ash, metakaolin, lime stone powder, steel slag powder, rice husk ash, nano particles, different aggregate sizes, super plasticizers and fibers. The above all mixed according to the design in optimum proportions and cured at room temperatures to obtain desire higher strength, toughness, and durability. These mixtures resulted in having compressive strength of 150-200 MPa. Due to the properties of new cement based material UHPC has got importance from around the world. Caijun et.al (2015), has reviewed about the hydration, microstructure, mechanical properties, stability and durability of UHPC. With the incorporation of steel fibers, UHPC has shown higher compressive strength and exposing to chlorides and sulfates due to low porosity and
has high resistance to extreme weather conditions. The hydration of ordinary concrete and cementitious materials in UHPC is almost similar. UHPC had a compacted interfacial transition zone without obvious pores due to the formation of reactive interface between incompletely hydrated core and hydrated products.

UHPC with steel fibers has shown greater splitting tensile strengths than usual when compared with ordinary concrete material. The cracking behavior of UHPC was not much influenced by sand to binder ratio and water to binder ratio but steel fiber had shown a difference compared to ordinary concrete. And also UHPC with steel had good resistance compared to one without steel fibers. The freezing and fire resistances of UHPC are better than ordinary concrete.

Allena and Newton (2010) has developed ultra-high strength concrete mixtures. Here the two mixtures used were one with steel fibers and other without. They have tested four specimens having different categories of preparation methods. They have studied about compressive strengths and flexural strengths of UHSC mixtures which were compared with the data available in literature. They have observed that the UHSC mixture with steel fibers has higher flexural strength and improvement in
ductility of concrete.

Table 2.6: Properties of UHSC mixtures (Allena and Newton (2010))

<table>
<thead>
<tr>
<th>Mixture</th>
<th>W/C ratio</th>
<th>50 mm cube Compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>7 days</td>
</tr>
<tr>
<td>UHSC without steel fibres</td>
<td>0.25</td>
<td>138.55</td>
</tr>
<tr>
<td>UHSC with steel fibres</td>
<td>0.25</td>
<td>146.06</td>
</tr>
</tbody>
</table>

2.5 Recycled concrete aggregates

In this section discussions on various researchers work done on Recycled concrete aggregate material and application of the material on RC beam to provide detailed understanding of literature review. Many experiments were conducted to study the behavior and flexural response of UHSC concrete beams.

There is a lot of rubble created when structures are demolished or renovated. This rubble was used to land fill in the foundation for strength. But when the rubble concrete is recycled and used in construction there were more advantages of keeping low construction cost and less environmental damage. The rubble collected is recycled and crushed into required aggregate sizes which are now good to use back in construction. The concrete strength, durability, and strength have been increased with the use of RCA.

However, use of recycled concretes in larger structures has not been practiced fully due to more impurity levels, lower compressive strengths and high variability in mechanical behavior. Hence, Tam et al. (2005) performed several experimental studies and proposed the Two-stage mixing approach (TSMA) mixing design, which was a good way for improving the compressive strength and lowering the mechanical behavior of recycled concrete aggregates compared to normal mixing approach. The observations made from different mixing approaches are shown in Table 2.7. The
results showed that fineness and removing impurities would improve the strengths of recycled concrete aggregates.

Table 2.7: Compressive Strengths and Percentages of Improvement in Different Proportions of RA Using NMA and TSMA (Tam et al. (2005))

<table>
<thead>
<tr>
<th>Mixing methods</th>
<th>Normal mixing approach (days)</th>
<th>Two-stage mixing approach (days)</th>
<th>Improvement % (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7</td>
<td>14</td>
<td>28</td>
</tr>
<tr>
<td>Compressive Strength (MPa)</td>
<td>0%</td>
<td>43.87</td>
<td>53.01</td>
</tr>
<tr>
<td></td>
<td>10%</td>
<td>50.29</td>
<td>54.53</td>
</tr>
<tr>
<td></td>
<td>15%</td>
<td>45.14</td>
<td>51.72</td>
</tr>
<tr>
<td></td>
<td>20%</td>
<td>42.21</td>
<td>51.92</td>
</tr>
<tr>
<td></td>
<td>25%</td>
<td>51.09</td>
<td>52.62</td>
</tr>
<tr>
<td></td>
<td>30%</td>
<td>45.49</td>
<td>54.58</td>
</tr>
</tbody>
</table>

The research on structural performance of RAC was first published in the Japan by Maruyama (2004), who performed testing on beams with 1.06% longitudinal reinforcement and used mixture proportions as listed in Table 2.8.

Table 2.8: Concrete mixture proportions (Maruyama et al. (2004))

<table>
<thead>
<tr>
<th>Concrete</th>
<th>W/C (W/B)</th>
<th>s/a (%)</th>
<th>w</th>
<th>c</th>
<th>Ex*</th>
<th>S</th>
<th>G</th>
<th>Pigment</th>
<th>Anti-former</th>
<th>SP*</th>
<th>AE*</th>
<th>AEWR*</th>
<th>$\frac{f_c}{N/mm^2}$</th>
<th>Age (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VC30</td>
<td>0.30</td>
<td>41.7</td>
<td>178</td>
<td>593</td>
<td>647</td>
<td>932</td>
<td>1.78</td>
<td>5.93</td>
<td>106.4</td>
<td>99</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CRC30</td>
<td>0.30</td>
<td>41.7</td>
<td>178</td>
<td>593</td>
<td>647</td>
<td>853</td>
<td>11.9</td>
<td>5.34</td>
<td>69.0</td>
<td>76</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CFRC30</td>
<td>0.30</td>
<td>40.8</td>
<td>177</td>
<td>588</td>
<td>543</td>
<td>870</td>
<td>11.8</td>
<td>10.6</td>
<td>53.8</td>
<td>99</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VC45</td>
<td>0.45</td>
<td>41.7</td>
<td>171</td>
<td>381</td>
<td>727</td>
<td>1048</td>
<td>2.28</td>
<td>57.0</td>
<td>60</td>
<td>60</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CRC-EX45</td>
<td>(0.45)</td>
<td>41.7</td>
<td>171</td>
<td>351</td>
<td>727</td>
<td>1048</td>
<td>3.08</td>
<td>55.3</td>
<td>61</td>
<td>61</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CRC45</td>
<td>0.45</td>
<td>41.7</td>
<td>171</td>
<td>381</td>
<td>727</td>
<td>958</td>
<td>7.61</td>
<td>0.76</td>
<td>46.5</td>
<td>88</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CRC-EX45</td>
<td>(0.45)</td>
<td>41.7</td>
<td>171</td>
<td>351</td>
<td>727</td>
<td>958</td>
<td>7.61</td>
<td>0.76</td>
<td>46.6</td>
<td>93</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CFRC45</td>
<td>0.45</td>
<td>41.8</td>
<td>170</td>
<td>378</td>
<td>625</td>
<td>960</td>
<td>7.55</td>
<td>2.27</td>
<td>35.5</td>
<td>70</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CRC-EX45</td>
<td>(0.45)</td>
<td>41.8</td>
<td>170</td>
<td>348</td>
<td>625</td>
<td>960</td>
<td>7.55</td>
<td>2.27</td>
<td>35.2</td>
<td>66</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VC60</td>
<td>0.60</td>
<td>47.7</td>
<td>187</td>
<td>311</td>
<td>840</td>
<td>935</td>
<td>1.56</td>
<td>40.2</td>
<td>105</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CRC60</td>
<td>0.60</td>
<td>47.0</td>
<td>164</td>
<td>292</td>
<td>859</td>
<td>848</td>
<td>5.84</td>
<td>1.28</td>
<td>32.9</td>
<td>41</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CFRC60</td>
<td>0.60</td>
<td>46.8</td>
<td>186</td>
<td>309</td>
<td>706</td>
<td>886</td>
<td>6.18</td>
<td>1.93</td>
<td>29.4</td>
<td>106</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Compressive strengths and splitting tensile strength were measured from samples according to JIS A 1108. The beams had the same pattern of plastic deformations and there were differences in deflections when compared to the beams with water/cement ratio of 0.3 and 0.45 to beams with Water/Cement ratio of 0.6. While the crack
spacings of recycled aggregates are smaller compared to RC beams, the moments calculated were larger than the measured values. Experimental observations in Table 2.8, showed flexural capacities of both beams do not have much difference between them, when the stress in the steel bars reach 200 N/mm².

Table 2.9: Flexural properties under serviceability condition when stress in RB reaches 200 N/mm² (Maruyama et al. (2004))

<table>
<thead>
<tr>
<th>concrete</th>
<th>W/C</th>
<th>Mcr (kNm)</th>
<th>I (mm)</th>
<th>W (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>I av</td>
<td>I max</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Exp.</td>
<td>Cal.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Exp.</td>
<td>Cal.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Exp.</td>
<td>Cal.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Exp.</td>
<td>Cal.</td>
</tr>
<tr>
<td>VC30</td>
<td>0.30</td>
<td>7.2</td>
<td>4.4</td>
<td>149</td>
</tr>
<tr>
<td>CRC30</td>
<td>0.30</td>
<td>4.5</td>
<td>4.4</td>
<td>141</td>
</tr>
<tr>
<td>CFRC30</td>
<td>0.30</td>
<td>3.7</td>
<td>3.6</td>
<td>114</td>
</tr>
<tr>
<td>VC45</td>
<td>0.45</td>
<td>4.3</td>
<td>4.7</td>
<td>145</td>
</tr>
<tr>
<td>VC-EX45</td>
<td>(0.45)</td>
<td>3.5</td>
<td>3.8</td>
<td>102</td>
</tr>
<tr>
<td>CRC45</td>
<td>0.45</td>
<td>2.1</td>
<td>2.6</td>
<td>101</td>
</tr>
<tr>
<td>CRC-EX45</td>
<td>(0.45)</td>
<td>4.5</td>
<td>5.3</td>
<td>127</td>
</tr>
<tr>
<td>CFRC45</td>
<td>0.45</td>
<td>4.5</td>
<td>4.2</td>
<td>107</td>
</tr>
<tr>
<td>CFRC-EX45</td>
<td>(0.45)</td>
<td>3.6</td>
<td>4.5</td>
<td>100</td>
</tr>
<tr>
<td>VC60</td>
<td>0.60</td>
<td>3.3</td>
<td>4.0</td>
<td>123</td>
</tr>
<tr>
<td>CRC60</td>
<td>0.60</td>
<td>2.7</td>
<td>2.9</td>
<td>99</td>
</tr>
<tr>
<td>CFRC60</td>
<td>0.60</td>
<td>2.4</td>
<td>3.0</td>
<td>130</td>
</tr>
</tbody>
</table>

Malesev, Radonjanin and Marinkovi (2010) has done an investigation on the recycled concrete aggregates which were prepared from the crushing of concrete cubes in the lab. They performed experimental analysis on the concrete beam made with 0%, 50% and 100% levels of recycled concrete aggregates. They have compared basic properties of concrete made with normal aggregates and concrete made with recycled aggregates. This research studied about 3 types of concrete as follows:

- Control concrete which used 100% natural river coarse aggregate.
- Control concrete having 50% natural river coarse aggregate and 50% of the recycled coarse aggregate.
- Control concrete 100% of recycled coarse aggregate.

All the three concrete types were made of same bulk density, water density, aggregate density and W/C ratios. The compressive strengths for all concrete types were done and showed similar strengths but RAC was having little higher strengths compared to control concrete mixture. Splitting tensile strengths measured has shown that control mixture with 0% and 100% RAC has similar values (2.6 MPa and 2.78 MPa) whereas 50% RAC has 3.2 MPa. Flexural strengths obtained were almost same for all three types of concrete mixtures. The modulus of elasticity measured shown control mixture with 35.55 GPA, RAC 50% with 32.25 GPA and RAC 100% with 29.10 GPA values. All the three types of mixtures have shown similar kind of stresses and deflections.

There were experimental investigations on the shear strength behavior of reinforced concrete beams with RCA. Mahdi, Smith, Volz, Khayat (2015), studied the shear strength of eight beams, in which four beams were 100% recycled concrete aggregates (RCA) while the rest of four beams were normal concrete (NC). The mix design of beams used aggregates with maximum nominal size of 25 mm which were made out of crushing the concrete material cured for 28 days and 46.1% residual mortar by mass. The shear reinforcement steel used was of ASTM A615-12 grade 60, (41 MPa) material and their mechanical properties were also tested. For flexural failure of concrete beams they have taken 2 different longitudinal reinforcement ratios (0.47% and 0.64%) into consideration and have applied, two point loading condition using hydraulic actuators, approximately with a load of 490 kN. They have plotted graphs for the mid-span load deflection curves, and shear strengths, based on their compressive strengths. From all the observations they made, crack propagation’s, and load deflection curves, for RAC and NC beams were displaying similar response. Whereas, RAC beams have lower shear strength compared to NC beams.
2.6 Self-compacting concrete

In this section, to provide detailed understanding of a review of self-compacting concrete material, and application of different admixtures were presented. We discuss different aspects such as stress parameters, ultimate strain, flexural responses, ductility, cracking, and deflections, applied with different loading conditions.

Malesev, Radonjanin and Marinkovi (2010), have investigated about the properties, and testing methods for determination of the self-compacting concrete. The design of SCC mix does not require any particular standard procedure.

<table>
<thead>
<tr>
<th>classification</th>
<th>Typical composition</th>
<th>Mixing efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free-fall mixers</td>
<td>Mixer drum and mixing blades</td>
<td>order</td>
</tr>
<tr>
<td>(tilting drum, drum mixers or gravity mixers)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forced action mixers</td>
<td>A vertical axis of rotation, cylindrical and horizontal pan (fixed or rotating), one or two sets of rotating blades</td>
<td>3</td>
</tr>
<tr>
<td>Pan mixers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pug mill mixers</td>
<td>A horizontal drum, one or two rotating horizontal shafts with attached blades</td>
<td>1</td>
</tr>
<tr>
<td>M-Y mixer (mixing by using gravity)</td>
<td>A set of mixing units but with no moving parts assembled into</td>
<td>2</td>
</tr>
</tbody>
</table>

The mix design has to fulfill three characteristics such as filling ability, passing ability and segregation resistance. The mentioned abilities were standard requirements for concrete mix to be known as self-compacting concrete. Each design mixture was followed by one or more test methods. The common test methods used to study the abilities of self-compacting concrete are as follows:

2.6.1 Slump flow test

This test is widely used for knowing the concrete capability of flowing under frictional force without any other obstructions. In this test, SCC is flowing on a plate
with the lift of slump cone as shown in fig 2.2. The filling ability of SCC depends on the T diameter of the circle. The time taken by the SCC to reach the diameter of circle is used to calculate the deformation capacity of mix.

![Slump flow test equipment](image)

Figure 2-2: Slump flow test equipment (Ferraris, 1999)

### 2.6.2 L-box test

![L-box test equipment](image)

Figure 2-3: L-box test equipment (Dietz, Ma, 2000)

L-box is made of two lengths vertical and horizontal. In this test the ability of SCC to flow or pass through the confined spaces like in between the reinforced bars which are in vertical length of box and into horizontal length of box as shown in fig 2.3. The passing ability is calculated by the ratios of heights (i.e $p=H_2/H_1$).
2.6.3 V-Funnel test

The assessment of filling ability and viscosity of SCC can be done using V-funnel test apparatus as shown in fig 2.4. In this test, SCC is poured into the funnel without any agitation and gate of the funnel are closed. A container is placed under the funnel to collect the SCC passed through the funnel. Open the gate after a time delay of (102)s from filling funnel we measure the time $t_v$ through the Amount of SCC flowing through the orifice. If the concrete is moving then stress is higher than yield stress or it is vice versa.

Figure 2-4: V-funnel test equipment (Dietz, Ma,2000)

Oladipupo, Adekunle, Abiodun, Adewale (2015), has studied about the densities, strength gains and compressive strengths of self-compacting concrete (SCC). The quantity of superplasticizer admixture was important in influencing the properties of SCC. Two series of SCC mixes were compared (0.5 and 0.38 water- cement ratios were used in SCC) in his work with the normal concrete with 0.5 W/C ratio. L-box test and V-funnel tests were done to study the rheological properties and results were not similar. The compressive strengths from cylinder specimens have shown
that strengths of control concrete were higher than SCC mixes at early ages, but SCC mixes has shown higher strength compared to control concrete after 90 days. They also observed that W/C ratios had a negligible effect on plastic properties of SCC when compared to control concrete.

As the importance of SCC was being exposed more in construction industry Yasser (2011) conducted series of experimental tests on the structural behavior of reinforced SCC beams.

Table 2.11: Details of SCC reinforced beam (Yasser (2011))

<table>
<thead>
<tr>
<th>Beam type</th>
<th>$f'_c$ (MPa)</th>
<th>As</th>
<th>A's</th>
<th>d (mm)</th>
<th>$d'$ (mm)</th>
<th>$\rho$</th>
<th>$\rho'$</th>
<th>$\rho / \rho_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCCB1</td>
<td>31.60</td>
<td>2φ14</td>
<td>2φ14</td>
<td>258</td>
<td>42</td>
<td>0.0059</td>
<td>0.0059</td>
<td>0.15</td>
</tr>
<tr>
<td>SCCB2</td>
<td>32.84</td>
<td>2φ20</td>
<td>2φ14</td>
<td>255</td>
<td>42</td>
<td>0.0123</td>
<td>0.0060</td>
<td>0.30</td>
</tr>
<tr>
<td>SCCB3</td>
<td>28.84</td>
<td>2φ18+2φ16+2φ14</td>
<td>2φ14 +2φ18</td>
<td>256</td>
<td>43</td>
<td>0.0168</td>
<td>0.0109</td>
<td>0.40</td>
</tr>
<tr>
<td>SCCB4</td>
<td>27.39</td>
<td>2φ20</td>
<td>2φ14 +2φ20</td>
<td>255</td>
<td>43.5</td>
<td>0.0246</td>
<td>0.0122</td>
<td>0.58</td>
</tr>
<tr>
<td>SCCB5</td>
<td>29.53</td>
<td>2φ22</td>
<td>2φ14 +2φ25</td>
<td>254</td>
<td>45</td>
<td>0.0299</td>
<td>0.0157</td>
<td>0.62</td>
</tr>
<tr>
<td>SCCB6</td>
<td>27.20</td>
<td>2φ28</td>
<td>2φ14</td>
<td>251</td>
<td>42</td>
<td>0.0490</td>
<td>0.0061</td>
<td>1.37</td>
</tr>
</tbody>
</table>

In his experimental investigations, he has used 6 simply supported reinforced SCC beams. Beams were tested with the application of step by step load using the testing machine. For compressive strengths, specimens were cast in 100 mm steel moulds having three samples for each.

Mid-span deflections and strain properties of beam were measured using linear voltage displacement Transducers (LVDT) strain gauges and values obtained shown in Fig 2.5. He has observed that the percentage of tension reinforcement ratios had made a difference in deflection and load bearing capacities rather than the compressive strengths of SCC.

A.A. Maghsoudi and Mehrab (2009) has done research on normal reinforced beam and SCC reinforced FEA modeling and experimental behavior of SCC beams. In this work they have studied about the graph of non-linear isotropic stress-strain of scc from the compression tests done in the laboratory. He has considered four simply supported reinforced SCC beams under two point incremental loading. LVDTs were
used in experimental setup to obtain different types of stresses and strains in beam at different locations.

Table 2.12: Details of tested beams (A.A. Maghsoudi and Mehrab (2009))

<table>
<thead>
<tr>
<th>Beam NO.</th>
<th>$f'_c$ (MPa)</th>
<th>$A_s$</th>
<th>$A'_s$</th>
<th>d (mm)</th>
<th>$d'$ (mm)</th>
<th>$\rho/\rho_b$</th>
<th>$\gamma_c$ (kN/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCCB1</td>
<td>33</td>
<td>2 φ 18 + 1 φ 16 + 1 φ 14</td>
<td>2 φ 14 + 1 φ 18</td>
<td>256</td>
<td>42.9</td>
<td>0.15</td>
<td>22.80</td>
</tr>
<tr>
<td>SCCB2</td>
<td>31.5</td>
<td>4 φ 20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SCCB3</td>
<td>35.0</td>
<td>4 φ 22</td>
<td>2 φ 14 + 1 φ 25</td>
<td>254</td>
<td>45.4</td>
<td>0.40</td>
<td>22.60</td>
</tr>
<tr>
<td>SCCB4</td>
<td>25.0</td>
<td>4 φ 28</td>
<td>2 φ 14</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For better understanding they have compared the mid-span deflection curves, cracking, yielding and ultimate loads of numerical and experimental SCC beams.

The results obtained by them have shown a good agreement with the experiment results. They found that SCC beams were having the slightly higher load carrying capacity and ductile nature when compared to normal concrete reinforced beam.

Also, SCC with high strength has shown different behavior when mixed with different admixtures by Jalal, Pouladkhan, Ramezanianpour, Norouzi (2012) have investigated on rheological and mechanical properties of high strength self-compacting concrete mixed with silica fume, silica nano powder and different binder contents.
Table 2.13: Details of different strengths of SCC specimens (Jalal (2012))

<table>
<thead>
<tr>
<th>No.</th>
<th>Concrete ID</th>
<th>Compressive strength (MPa)</th>
<th>Splitting tensile strength (MPa)</th>
<th>Flexural strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>7 days</td>
<td>28 days</td>
<td>90 days</td>
</tr>
<tr>
<td>1</td>
<td>SCC400</td>
<td>36.4</td>
<td>51.8</td>
<td>53.1</td>
</tr>
<tr>
<td>2</td>
<td>SCC450</td>
<td>36.4</td>
<td>52</td>
<td>53</td>
</tr>
<tr>
<td>3</td>
<td>SCC500</td>
<td>40.2</td>
<td>52.5</td>
<td>53.2</td>
</tr>
<tr>
<td>4</td>
<td>SCC400 NS2%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>SCC450 NS2%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>SCC500 NS2%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>SCC400 SF10%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>SCC450 SF10%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>SCC500 SF10%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>SCC400 SF10NS2%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>SCC450 SF10NS2%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>SCC500 SF10NS2%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

They have used poly-carboxylic ether based super plasticizer, viscosity modifying agent and powder materials (like cement, silica and nano silica) for SCC mix design. For compressive strengths and splitting tensile strengths determination, the cubic and cylindrical moulds of SCC prepared were moistened for 48 h by polyethylene sheets. The samples for each mix on 7, 28 and 90 days were cured and obtained different strength results as shown in Table 2.13. The results of strengths have shown that rheological properties of all mixes increased with increase in binder content of the paste.
Chapter 3

Calibrated Normal Strength RC Beam with Various Cementitious Materials

3.1 Introduction

The following finite element analysis approach was used for modelling all simulations of RC beams. Experimental and analytical investigations were carried out to study the flexural behavior of the control reinforced concrete beam (Chahrour and Soudki 2005) compared to the results of the FEA modeled control beam. FEA modeling methods for different element types, loading conditions and meshing geometries of reinforced concrete materials were discussed. The different cementitious material properties obtained from the literature were used in the F. E control beam to analyze the behavior of the model in flexure (respective comparisons of mid-span load deflection curves were presented in this chapter).
3.2 Calibration of Normal Strength RC Beam

For validation of Normal Strength RC Beam model, the experimental RC model under consideration in this numerical study, is the one proposed by (Chahrour and Soudki 2005). They have tested reinforced concrete beam for four points bending.

![Diagram of Calibrated Normal Strength RC Beam and reinforcement details](Image)

The beam was rectangular in shape having length - 2400 mm, width - 150 mm, depth - 250 mm and was reinforced with two different types of steel bars. The tension zone was reinforced with 15 M steel bars and the compression zone was modeled with 6M steel bars. The geometry and the test set-up of the experiment are as shown in Figure 3.1. Chahrour and Soudki (2005) have mentioned that they have used an
excess amount of shear reinforcement in order to make sure that beam does not fail in shear according to Canadian Standards Association (CSA) standard A23.3-94 (CSA 1994).

The steel plates were used to clench the supports for the not loaded side of the specimen at the corners, having pinned support at one corner and roller support at the other. The experiment is modeled using the displacement-control method, where the displacement is applied at the edge of the bars through the concrete blocks. Now the specimen is scaled into a testing machine. In the experiment, A servo-controlled ESH-1000 kN universal testing machine was used to apply loads.

### 3.3 modeling of Element types

Different material models and element types are available in ANSYS, the materials considered for simulation purposes are discussed in this section. Then the element and material types used for each part of the model is described in detail.

#### 3.3.1 Solid65

In order to better simulate the different types of concrete elements, the solid65 element was used for concrete as its distinct properties, like crushing strength in compression and cracking in tension, are modeled by smeared crack approach. The element is also capable of being modeled with or without reinforcement (ANSYS, 2008). The solid65 element is an 8 node element with three degrees of freedom, having a translation in all three directions at each node. Treatment of this element with nonlinear material properties is the most important feature that makes it popular. The capability of concrete in cracking, crushing, plastic deformation and creep makes this element a powerful tool for modeling concrete elements. The condition of crack face is represented by the coefficient of shear transfer ($\beta_t$) which ranges from 0.0 (for
smooth crack) to 1 (rough crack). These values must be adjusted in such a way that it does not produce any convergence issues.

![Solid65 geometry](image)

Figure 3-2: Solid65 geometry (ANSYS, 2013)

<table>
<thead>
<tr>
<th>Material type</th>
<th>Elements in ANSYS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>Solid65</td>
</tr>
<tr>
<td>Steel reinforcement</td>
<td>Beam 188</td>
</tr>
<tr>
<td>Steel plates</td>
<td>Solid45</td>
</tr>
</tbody>
</table>

Table 3.1: Assigning of elements

Concrete behavior varies in compression and tension due to its quasi-brittle material nature. The tensile strength of concrete is typically 8-15% of the compressive strength (Shah et al. 1997). Figure (3.3) shows a typical stress-strain curve for normal concrete (Bangash 1989).

Normally about 30% of the maximum compressive strength, the concrete curve is linearly elastic in the compression zone. In fig 3.3 the curve enters into softening region right after the peak compressive stress, while crushing of concrete material begins. The failure of material occurs at the point where curves reach the ultimate strain...
\( \epsilon_u \). But the linear elasticity nature of stress-strain curve of concrete only lasts till it reaches maximum tensile strength and, after that point, concrete cracks attaining zero strength (Bangash 1989). According to Wolanski (2004) the behavior of concrete depends on the values of linear and multi-linear isotropic material properties assigned to solid elements to converge properly. The linear isotropic material properties assigned to current concrete model are displayed in Table (3.2). The multi-linear isotropic properties computations obtained are needed for knowing the compressive uniaxial stress-strain relationship for the concrete model. The required properties are calculated based on the following equations (3.1) and (3.2) proposed by Desayi and Krishnan (1964) and equation (3.3) proposed by Gere and Timoshenko (1997).

\[
f = \frac{(E_c \epsilon)}{1 + (\epsilon/\epsilon_o))} \tag{3.1}
\]

\[
\epsilon_o = \frac{(2f_c')}{(E_c)} \tag{3.2}
\]
\[ E_c = \frac{f}{\epsilon} \]  \hspace{1cm} (3.3)

Where:
\[ f = \text{stress at any strain } (\epsilon), \text{ Mpa} \]
\[ \epsilon = \text{strain at stress } f \]
\[ \epsilon_o = \text{strain at the ultimate compressive strength } (f'_c) \]
\[ E_c = \text{Modulus of elasticity of Concrete} \]

Figure 3-4: Concrete compressive uni-axial stress-strain curve Wolanski (2004)

The simplified stress-strain curves for each beam model were created based on the six points, connected by straight lines. The curve in fig 3.4 starts from zero stress and strain values. The First point in the curve is obtained by 0. 30f'_c which is calculated in the linear range by equation (3.3), for the stress-strain relationship of concrete. The points 2, 3 and 4 are calculated using the equation (3.1) and strain at ultimate strength (\( \epsilon_o \)) is obtained using equation (3.2). The ultimate compressive strength corresponding to strain at ultimate strength is used for plotting a point five in the curve. The Uni-axial stress-strain values of curves for different cementitious materials.
are plotted in Figure 3.5.

![Graphs showing uniaxial stress-strain values for different types of concrete](image)

Figure 3-5: Uniaxial stress-strain values of curves for (a) Control concrete (b) Fly ash (c) Ultra high strength concrete (d) Recycled aggregate concrete (e) Self-compacting concrete

### 3.3.2 Beam188

Beam188 is the element type used for flexural and shear reinforcement in this FEA modeling. Steel rebars and stirrups were included in the concrete element for simulating compressions and tensions. The nodes are used for modeling the reinforcing elements in this simulations. These steel bars are modeled in ANSYS using the beam188 element. The Beam188 element is suitable for analyzing thick beam structures. This is a linear (2-node) beam element in 3-D with six degrees of freedom at each node. They can be translated and rotated in X, Y, and Z directions. The Eigen value buckling or collapse studies with arc length methods are used to
study the stiffness of the beam elements resulting in analysis of flexural, lateral and torsional stability problems. This element is very suitable to model all types of elasticity and isotropic hardening plasticity models. Linear finite strain, integration points, and cross-section of the beam element is shown in fig 3.6.

In FEA models, the Von-Mises yield criteria are used for steel bars and stirrups as they are assumed to be elastic-perfectly plastic materials. For stress-strain curves of the materials as shown in Figures (3.10) and (3.12), bilinear isotropic hardening (BISO) material was used for simulation purposes which mean during the plastic flow yield surface deforms uniformly as shown in fig 3.7. The properties of flexu-
ral reinforcement and shear stirrups include modulus of elasticity, tangent modulus, yielding stress and strain. Where modulus of the tangent is 0.01 times the modulus of elasticity, according to Haider M. Abdul Hussein and Ahmed N. Mohammed (2013).

![Bilinear isotropic hardening model](image)

Figure 3-7: Bi-linear isotropic hardening model (ANSYS 2008)

### 3.3.3 Solid45

The Solid45 element is used to model steel plates for applying the point load uniformly. Steel plates are used to maintain constant stresses throughout the thickness of the plate. This element is used for the design of 3-D solid structures as seen in fig 3.8. To avoid premature failure of crushing the concrete, steel plates were modeled in the simulation at point of sharp loading conditions and support reactions. Applying the load on steel plates helps in solving the convergence issues in ANSYS to avoid crushing of concrete cover just below the point of load application. The material properties of steel plates are similar to steel reinforcement. The size of the steel plate at the point of application of loads and supports are 150mm * 150mm and 75mm*150 mm respectively, with a thickness of 10mm. The steel plates were glued with the RC-beam by merging the common nodes.
3.3.4 Failure criteria of concrete

The solid65 element has the capability to analyze the failure of concrete materials, both in compression and tension. The ultimate compressive and uniaxial strengths are the two strength parameters needed to be defined for the prediction of failure criteria of concrete material model. Once principal tensile stresses in any direction exceed the maximum tensile principal stresses of concrete, the concrete material starts to cracking. Similarly, once principal compressive stresses exceed the maximum compressive stresses of concrete, concrete material starts crushing. ANSYS has the ability to remove cracked or crushed elements, to run the analysis further more after cracking.
has initiated. To deactivate these cracked or crushed elements, the elastic modulus of elements, which are cracked, is set to zero.

![Failure surface for concrete in stress state (ANSYS 2014)](image)

Figure 3-10: Failure surface for concrete in stress state (ANSYS 2014)

The William and Warnke (1975) five parameter material model criterion is adopted for analyzing the constitutive model and to define the failure surface of concrete material due to tri-axial stresses (default parameters used by ANSYS). William and Warnke required five parameters, which according to different failure modes, are as follows:

- Ultimate uniaxial tensile strength
- Ultimate uniaxial compressive strength
- Ultimate biaxial compressive strength
- Tensile meridian
Compressive meridian

The values of shear transfer coefficients for open and closed cracks are determined by the behavior of the solid65 element in shear. The concrete remains in linearly elastic condition before it fails and loses its stiffness when it cracks or crushes. The Rankin failure condition is used for tension cut-off during the condition of pure tension. Usually, concrete cracking is permitted in any direction at each integration point. For failure criteria of concrete, shear transfer coefficient for open and close cracks ($\beta_o$ and $\beta_c$), uniaxial tensile stress and uniaxial crushing stress are considered. The failure criteria of concrete are governed by uniaxial tensile stress and uniaxial crushing stress, which are obtained from the experimental data. For crack face condition, shear transfer coefficients ($\beta_t$) are to be considered.

![Figure 3-11: Concrete stresses in cracked condition (ANSYS 2012)](image)

3.4 Material properties

The suitable material model and element types are selected depending on the behavior of material types, accuracy of the solution, convergence criteria and computational time for a solution. In this section, modeling of different material properties
for reinforced concrete, fly ash concrete, recycled concrete aggregates concrete, ultra high strength concrete, flexural reinforcement, steel bars, steel plates and their finite element discretization are discussed. The solid65 element is used for modeling different types of concrete materials. This element has unique material properties which are, cracking in tension and crushing in compression, as discussed earlier. The material properties needed to be assigned to the concrete are linear isotropic and multilinear isotropic material properties. The modulus of elasticity \( E_c \), Poissons ratio \( \nu \) and splitting tensile strengths \( f_t \) are also calculated based on the compressive strengths of concrete material for simulation purposes and their relationship is defined in equations (3.4) and (3.5) according to ACI code (ACI-318) as follows:

\[
E_c = 4700 \times \sqrt{f_c'} \quad (3.4)
\]

\[
f_t = 0.7 \times \sqrt{f_c'} \quad (3.5)
\]

The parameters considered were all in mega pascal (MPa). Poissons ratio is assumed between 0.15-0.3. Von-misses criteria are considered along with William Warnke (1975) model for the multi-linear isotropic properties of material model. Different cementitious material properties of concrete considered for the calibration purposes are shown in Table 3.2.

<table>
<thead>
<tr>
<th>ID</th>
<th>Compressive strength ((f_c')) MPa</th>
<th>Modulus of elasticity ((E_c)) MPa</th>
<th>Poissons ratio ((\nu))</th>
<th>(\beta_t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Beam (CB)</td>
<td>39</td>
<td>28100</td>
<td>0.25</td>
<td>0.2</td>
</tr>
<tr>
<td>Fly ash beam (C1)</td>
<td>31.6</td>
<td>26000</td>
<td>0.25</td>
<td>0.15</td>
</tr>
<tr>
<td>UHSC (C2)</td>
<td>161.9</td>
<td>59800</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>RCA 50 (C3)</td>
<td>35.5</td>
<td>28200</td>
<td>0.25</td>
<td>0.2</td>
</tr>
<tr>
<td>RCA 100 (C4)</td>
<td>34.09</td>
<td>27450</td>
<td>0.25</td>
<td>0.2</td>
</tr>
<tr>
<td>SCC (C5)</td>
<td>31.5</td>
<td>26000</td>
<td>0.24</td>
<td>0.25</td>
</tr>
</tbody>
</table>
*Compressive strengths at 28 days

3.5 FEA Modeling

The FEA modeling of RC structures was performed using ANSYS. In this modeling, the whole beam was modeled and volumes are used for creating the concrete beam, supports, and steel plates. ANSYS provides analysis on structural preferences based solutions using the iterations combined with the element type, non-linear elements, material laws and inelastic material models.

3.5.1 Linear isotropic and multi-linear isotropic material properties for control beam:

Table 3.3: linear isotropic material properties

<table>
<thead>
<tr>
<th>Parameters</th>
<th>RC beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus ($E_c$)</td>
<td>28.1</td>
</tr>
<tr>
<td>Poissons ratio (v)</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Table 3.4: Multi-linear isotropic material properties

<table>
<thead>
<tr>
<th>parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of Rupture</td>
<td>4.371 MPa</td>
</tr>
<tr>
<td>Open Shear Transfer Coefficient</td>
<td>0.2</td>
</tr>
<tr>
<td>Closed Shear Transfer Coefficient</td>
<td>0.2</td>
</tr>
<tr>
<td>Uniaxial Crushing Stress</td>
<td>-1</td>
</tr>
<tr>
<td>Shear Transfer Coefficient</td>
<td>0 to 1</td>
</tr>
<tr>
<td>Open crack ($\beta_0$)</td>
<td>0.2</td>
</tr>
<tr>
<td>Closed crack ($\beta_C$)</td>
<td>0.2</td>
</tr>
<tr>
<td>Compressive Strength of Concrete</td>
<td>39 MPa</td>
</tr>
</tbody>
</table>

*Uni-axial Crushing Stress: -1 (neglecting Crushing Effect to stabilize the convergence)
Steel plates were used in this beam model at point of loading and support conditions in order to maintain stability and avoid crushing of concrete cover at the point of sharp loading conditions.

### 3.5.2 Flexural Reinforcement

The material properties as provided in experiment are as follows:

- Modulus of Elasticity ($E_c$) = 200 GPa
- Yield Strength = 400 MPa
- Poisson’s ratio = 0.25
- Tangential Modulus $E_s' = 0.01 \times E_s$ (Sergiu et al. (2011), Kachlavek et al. (2001), Wolanski (2004))

$$E_s' = 200 \times 1000 \text{ MPa} \times 0.01 = 2000 \text{ MPa (Bilinear kinematic hardening model (BKIN))}$$

Bottom rebar size= 2-15M equivalent to 2-16mm diameter bar Top rebar size= 2-6M equivalent to 2-6 mm diameter bar
3.5.3 Shear Reinforcement

Beam188 element is used for modeling Rebar. The material properties of shear stirrups according to the experiment as follows:

Modulus of Elasticity \( (E_s) = 200 \) GPa

Yield Strength = 300 MPa
Poisson’s ratio = 0.25

Tangential Modulus $E'_{s} = 0.01E_{s}$ (Sergiu et al. (2011), Kachlakev et al. (2001), Wolanski (2004))

Stirrup Size = 6M equivalent to 6 mm, Spacing are shown in Figure 3.1.

Figure 3-15: FEA model side view for Steel bars

3.6 Mesh modeling

For computing and analyzing the stresses in reinforced concrete accurately, every volume of concrete is divided into a number of small elements and meshed as shown in fig 3.14. The rectangular shape mesh is recommended for solid65 elements. In finite element modeling, the step for selection of mesh density was selected on basis of shear stirrup spacing and longitudinal rebar location for concrete elements which was adjusted between finer and coarser to get the possible best result. The adequate number of elements in mesh analysis, would help in converge of results. This is practically achieved when an increase in the mesh density has a negligible effect on the results (Adams and Askenazi 1998). The steel elements do not need meshing
especially, as they were created individually through the nodes created by the mesh of concrete volume (Wolanski 2004).

![Figure 3-16: Mesh modeling](image)

### 3.7 Loading and boundary conditions

The reinforced concrete beam used in finite element analysis is a simply supported beam according to the experimental configuration. The left end of the beam is hinge support constrained in horizontal and vertical direction, whereas right end is roller support constrained in vertical direction. The two-point bending loads were applied on top of steel plates in the form of constant pressure load with respect to areas of steel plates as shown in Figure 3.15. The steel plate and concrete in the beam are assumed to have a perfect bond between them. For purposes of simulation and faster solutions, some of the nodes are attached together and perfect bond is assumed between the elements.
3.8 Results of FEA Analysis

The model used for finite element analysis of reinforced concrete beam was considered similar to the experimental model in order to analyze the accuracy of the developed model. Finite element model was developed by using ANSYS APDL 14.5. In this section, we studied different ideas based on the experimental model and in the majority of cases large displacements are neglected. These different ideas include cracking and crushing of concrete, Mid-span load displacement curve and failure load criteria.
3.8.1 Cracking and crushing of concrete

The linear region is analyzed by many researchers (Gregor 1992; Hemmaty 1998) based on the flexure design of reinforced concrete beam model. The FEA control beam model before cracking needs to be ensured such that the applied loads are consistent. In order to obtain the data, stresses were analyzed right after the cracking of concrete and steel. The values of crushing load of concrete, stresses, deflection of beams with different substitutes of concrete material are obtained from finite element analysis (from ANSYS). The comparison of values is presented in Table 3.5.

<table>
<thead>
<tr>
<th>Model</th>
<th>Concrete First Cracking Load (kN)</th>
<th>First Cracking Load Deflection (mm)</th>
<th>Modulus of rupture (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB</td>
<td>22</td>
<td>1.43</td>
<td>4.73</td>
</tr>
<tr>
<td>C1</td>
<td>24</td>
<td>1.75</td>
<td>3.92</td>
</tr>
<tr>
<td>C2</td>
<td>22</td>
<td>1.65</td>
<td>2.65</td>
</tr>
<tr>
<td>C3</td>
<td>22</td>
<td>1.28</td>
<td>3.03</td>
</tr>
<tr>
<td>C4</td>
<td>43</td>
<td>2.11</td>
<td>9</td>
</tr>
<tr>
<td>C5</td>
<td>26</td>
<td>1.5</td>
<td>3.73</td>
</tr>
</tbody>
</table>

CB- control beam, C1- CB with 25% fly ash, C2- CB with UHSC, C3&4- CB with RCA50, 100, C5- Self-compacting concrete

3.8.2 Non-linear solution

In nonlinear solution, a sequence of load increments of the total load was applied. In ANSYS Newton-Raphson method was selected for iteration and proper convergence of solution at each load step. This model was based on displacement and applied pressure. So for this purpose of convergence loads were applied using a number of sub-steps. The option of the automated load was selected in solution controls, increasing the loads in step by step manner on the structure.
3.8.3 Behavior of initial crack patterns

In ANSYS, the patterns of cracks are obtained using the plot option of crack/crushing. There is also an option for plotting integrated points of concrete solid elements. Principal tensile stresses when exceeds the ultimate tensile strength of concrete cracking during initiation which we can be observed from the sign represented as circle in the model.

![Crack plane sign and Integration points in concrete (ANSYS)](image)

The first cracking of the finite element concrete model occur at a load of 21.76 kN due to exceeding modulus of rupture of the model (4.371 MPa) as shown in Table 3.5. In Figure 3.18 we can see the first crack sign in control beam model which is a flexural crack where moment region is constant. The cracking load of the experimental beam was considered according to Ali chahrour and Khaled soudki (2005). The modulus elasticity of concrete element which is parallel to direction of principal stresses is set to zero after cracking was initiated. When all the principal and compressive stresses are in the outer region of failure region, the crushing of concrete model starts. Elements
disappear when the modulus of elasticity is zero.

In the compressive crack zone, the circle appears to be perpendicular to the principal strains in element near the loading locations at integrated points.

At each load, step evolution of cracks is noticed and kept for the records by ANSYS. As loads applied at each step increases, the cracks start to appear under the applied loads and the flexural cracks from mid-span spread to fixed support end. On the hand, the tensile cracks appear at the higher loads and compressive cracks appear near the maximum applied loads. The comparison of experimental concrete beam by chahrour and soudki (2005) for applied load of 110 kN and FEA analysis by Ansys with different substitutes of concrete has shown good agreement with experimental beam results. At the failure load of reinforced concrete beam, tensile stresses are
higher and result in (a) evolution of cracks, (b) flow direction stresses in concrete, (c) steel bar stresses, (d) tensile forces in steel bar as shown in Figure 3.21.

Figure 3-21: (a) Evolution of cracks, (b) Flow direction stresses in concrete, (c) Steel bar stresses due to concrete, (d) Tensile forces in steel bar (Nilson, 1997).

### 3.9 Midspan load deflection plots

Three linear variable displacement transformers were used to measure the vertical deflection of the experimental control beam at mid-span. The loading was done on two point loading basis. For ANSYS, the loads were applied as the experimental beam to measure the load deflection. For validation purposes, the load deflection
curves for the experimental beam tests (Chahrour and Soudki 2005) and the finite element analysis have been plotted in Figure 3.23 This plotting has shown that the results obtained from Finite element analysis were in close agreement with each other. Hence, different substitutes of concrete were studied and analyzed. In the Figures [3.21- 3.24] shows the vertical mid span load deflection plots of FEA control beam with experimental control model, fly ash , recycled concrete aggregates, and ultra-high strength concrete (without steel fibers) beams are discussed in following cases.
Case 1: Comparison of validated model

Figure 3-23: Mid span Load deflection plot for control beam

The mid-span load deflection plots of experimental control RC beam and FEA control RC beam are shown in Figure 3.23. In this analysis, the first cracking load occurs at 21.87 kN and in an experiment at 19 kN which is lower load than finite element analysis results by 14%. The steel yielding of finite element model occurs at 87.28 kN with deflection of 9.26 mm Y-direction, whereas for experimental occurs at 83.5 kN and with deflection of 9.12 mm from the end of the beam. The ultimate deflection of the finite element model is 43.30mm occurs at a load of 102.16 kN whereas for experimental is 44.82 mm at 106.50 kN showing that experimental beam ultimate load is higher than the finite element beam by 4%.

Case 2: Comparison of validated FEA model and FEA control beam with fly ash

Figure 3.24 shows the mid-span load-deflection plots for the properties of FEA control beam with 25% fly ash (A.A. Ramezanianpour (1996)) and FEA control
Figure 3-24: Mid-span Load deflection plots for FEA control RC beam with 25% fly ash

model. The results of finite element analysis have shown that the first cracking load for fly ash beam occurs at 18.14 kN and in FEA control beam at 21.87 kN which is lower load than finite element analysis results by 11%. The steel yielding of finite element fly ash beam model occurs at 81 kN with a displacement of 7.86 mm in vertical direction. The ultimate deflection of the finite element fly ash model is 44.7 mm occurs at load of 101.50 kN. The observations show that FEA control beam and the finite element fly ash beam ultimate loads are similar. The ultimate deflection of fly ash beam is higher than the FEA control beam by 6%.

Case 3: Comparison of validated FEA model and FEA control beam with recycled concrete aggregates

Figure 3.25, shows the mid-span load-deflection plots for the properties of beam constructed with 50 and 100% (RCA) ((Mahdi, Drury, Jeffery, and Kamal (2015)) and finite element control model. In results of finite element analysis, the first cracking
load of beams with RCA 50 and 100% occurs at a same load of 22 kN and in FEA control beam at 21.87 kN. The steel yielding of finite element model with RCA 50% and 100% occurs at 89 kN and 83.8 kN with deflection of 9.17 mm and 8.71 mm in the vertical direction. The ultimate deflection of the finite element model with RCA 50 and 100% is 44 mm and 44.3 mm occurs at loads of 102.30 kN and 101.55 kN. The observations show that FEA control beam and the finite element of RCA beam with different mixtures ultimate loads are similar. The ultimate deflection of RCA 100% beam is higher than the FEA control beam by 5%.

**Case 4: Comparison of validated FEA model and FEA control beam with Ultra high strength concrete material**

Figure 3.26 shows the mid-span load-deflection plots for FEA Ultra High Strength Concrete (UHSC) beam model of experimental (Allena and Newton (2010)) and control RC beam. In this finite element analysis, the first cracking load for UHSC occurs
Figure 3-26: Mid-span Load deflection plots for FEA Control beam and UHSC beam at 42 kN and in FEA control beam at 21.87 kN.

Case 5: Comparison of validated FEA control model and FEA control beam with SCC mixture

The curves plotted from finite element analysis in the above-mentioned Figure 3.27 has shown that the first cracking load for a beam with SCC occurs at 25.84 kN and in FEA control at 21.87 kN which is lower load than finite element analysis results by 18%. The steel yielding of finite element SCC model occurs at 89 kN with displacement of 8.69 mm in the vertical direction. The ultimate displacement of the finite element SCC model is 41.65 mm occurs at a load of 103.13 kN.
3.10 Analysis of the results

The linear solution for mid-span load deflection curves obtained from the experimental data and the finite element modeling methods (Figure 3.28, and Table 3.6) has not shown the similar behavior in pre-cracking elastic stages, but the steel yielding loads of cementitious materials were narrowly different. Two cementitious materials, SCC and UHSC, have shown higher cracking loads with less deflections. The experimental data and the finite element method beams stiffness show same behavior prior to pre-cracking with linear response. After the post cracking of concrete, the experiment beam has a less stiffness compared to the finite element model.
Figure 3-28: Mid-span load deflection plots for FEA RC beam with various cementitious mixtures

Table 3.6: FEA results summary of Control Beam with Different cement mixtures

<table>
<thead>
<tr>
<th>Model ID</th>
<th>Ultimate Load (kN)</th>
<th>Steel yielding Load (kN)</th>
<th>Deflection of steel yielding (mm)</th>
<th>Ultimate displacement at mid-span (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB</td>
<td>102.16</td>
<td>87</td>
<td>9.26</td>
<td>43.6</td>
</tr>
<tr>
<td>C1</td>
<td>101.30</td>
<td>88</td>
<td>10.23</td>
<td>44.6</td>
</tr>
<tr>
<td>C2</td>
<td>100.15</td>
<td>87</td>
<td>9.17</td>
<td>45.01</td>
</tr>
<tr>
<td>C3</td>
<td>100.23</td>
<td>86.6</td>
<td>10.9</td>
<td>45.4</td>
</tr>
<tr>
<td>C4</td>
<td>110</td>
<td>91</td>
<td>6.76</td>
<td>37.25</td>
</tr>
<tr>
<td>C5</td>
<td>103.13</td>
<td>89</td>
<td>8.69</td>
<td>41.65</td>
</tr>
</tbody>
</table>

CB- control beam, C1- control beam with 25% fly ash, C2 & 3- Control beam with RCA 50% & 100%, C4- Control beam with UHSC, C5- control beam with SCC.
Chapter 4

Calibration of High strength Self-compacting Concrete

4.1 Introduction

For validation of the high Strength SCC Beam model, experimental investigations and F. E modeling validation techniques of the self-compacting concrete beam are presented. This chapter analyzes the experimental and finite element modeling design procedures of the self-compacting concrete beam proposed by A.A. Maghsoudi, E. Hosseini Mehrab (2009). Necessary changes made in material properties and FEA modeling methods of different element types, loading conditions, and meshing geometries are discussed. In the following analysis, we also present the results on rheology of high strength SCC beam effected with silica nano powder and silica fumes.

4.2 Calibration of High Strength SCC Beam

For the validation of high strength SCC beam, the experiment under consideration in this numerical study is the one proposed by (Maghsoudi and Mehrab (2009)). They have tested a high strength reinforced SCC beam under two-point bending, and
provided with 25 mm of clear cover. The beam was rectangular in shape, having a length of 3000 mm, width of 200 mm, and depth of 300 mm, which was reinforced with two different types of steel bars. The tension zone and compression zone were reinforced with 20 mm diameter steel bars. 10 mm diameter shear stirrups were provided. The geometry and the test set-up of the experiment are shown in Figure 3.2. Author mentioned that they used an excess amount of shear reinforcement in order to make sure that the beam doesn’t fail in shear.

Figure 4-1: Calibration and reinforcement details of high strength SCC beam
4.3 Finite element analysis

Finite element modeling of self-compacting concrete was performed using ANSYS computer software program. To study response of SCC structural preferences, similar methods of reinforced concrete material models from chapter 3 were utilized. For a better understanding of this structure, results of the FEA model and experimental results are validated.

Necessary steps were taken: modeling size, boundary conditions, and loading conditions for accurate results. In the following section, different parameters and material properties used for nonlinear solution of the model are described in detail.

4.4 Material properties

Solid65 is the same element used for modeling self-compacting concrete material. This model used similar properties of the calibration model for steel reinforcements, steel plates at loading, and supports. Material properties of different materials used in these simulations are shown in Table 4.1.

Table 4.1: Material Properties

<table>
<thead>
<tr>
<th>ID</th>
<th>Compressive strength ($f'_c$) (MPa)</th>
<th>Modulus of elasticity (Ec) (MPa)</th>
<th>Poissons ratio (v)</th>
<th>$\beta_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control SCC beam</td>
<td>31.5</td>
<td>26400</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>scc450</td>
<td>52</td>
<td>34000</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>SCC450 SF10%</td>
<td>80.4</td>
<td>42000</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>SCC450 NS2%</td>
<td>58.3</td>
<td>36000</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>SCC450 SF10%NS2%</td>
<td>83.5</td>
<td>43000</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

SCC450-self-compacting concrete with 450 kg/m³ binder content
Table 4.2: Uniaxial stress-strain values for control SCC beam

<table>
<thead>
<tr>
<th>Strain</th>
<th>Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.0004</td>
<td>9.45</td>
</tr>
<tr>
<td>0.0008</td>
<td>17.96</td>
</tr>
<tr>
<td>0.0012</td>
<td>24.51</td>
</tr>
<tr>
<td>0.0016</td>
<td>28.66</td>
</tr>
<tr>
<td>0.002</td>
<td>30.88</td>
</tr>
<tr>
<td>0.0024</td>
<td>31.50</td>
</tr>
</tbody>
</table>

Figure 4-2: Uni-axial stress-strain curve for Control SCC beam

Steel bar
The material properties as provided in the experiment are as follows:

Modulus of Elasticity (Ec) = 200 GPa

Yield Strength = 400 MPa

Rebar size= 4-20 mm diameter bars

Stirrups

Modulus of Elasticity (Es) = 200 GPa

Yield Strength = 300 MPa

Stirrup Size= 10 mm diameter
4.5 Finite element model of reinforced SCC beam

The whole beam is modeled similarly to the FEA reinforced concrete model from chapter 3. The model was developed using the same dimensions as the experimental beam by (Jalal et.al (2012)). For simulation purposes, steel plates, with a width of 10mm, were created at the point of loading with dimensions 200mm*200mm.

Figure 4-3: FEA model side view for Steel bars

Figure 4-4: Finite element model of SCC Beam
4.6 Results of FEA SCC beam with different admixtures

To ensure accuracy of results, FEA analysis of the high strength self-compacting concrete (SCC) beam was compared with the experiment model in previously published research. The concrete crushing and steel yieldings were plotted in these simulations using the ultimate strain, of concrete and steel, material values according to ACI 318-11. In this section, Load deflection curves for high strength SCC beam with silica nano powder and silica fumes were plotted using previous studies. The properties of the SCC beam proposed by (Jalal et.al, (2012)), is considered and comparisons are made with finite element analysis of control the SCC beam modeled in this studies.

Case 4.5.1: Validation of FEA control SCC beam model

![Load deflection curves for experimental SCC and FEA SCC](image)

Figure 4-5: Deflection plots for experimental SCC and FEA SCC
In above Figure 4.5, Shows the mid-span load deflection plots for the SCC control beam (A.A. Maghsoudi 2009), which was compared to the finite element analysis model in this research. In this finite element analysis, the first cracking load of FEA control SCC beam model occurs at a load of 24.22 kN and in an experiment at 23.96 kN. The experimental SCC beam was crushed earlier than the finite element beam analysis results. The steel yielding of the finite element model occurs at 198.43 kN with a displacement of 9.96 mm, whereas for the experimental SCC beam yielding occurs at 194.22 kN with a displacement of 9.67 mm in the vertical direction. The ultimate deflection of the finite element model is 40.60 mm, which occurs at a load of 237.32 kN, whereas for the experimental SCC beam the deflection is 41.94 mm, occurs at a load of 230.80 kN.

Case 4.5.2: FEA control SCC beam model with SCC450

![Figure 4-6: Mid-span Load deflection plot for FEA control beam and SCC450](image)

In Figure 4.6, load-deflection plots of self-compacting concrete (SCC) with a total binder content of 450 kg/m³ and FEA SCC beam were done and has demonstrated
reasonably similar curves. In this finite element analysis, the first cracking load of SCC occurs at 25.44 kN and SCC450 at 27.89 kN, which illustrates a 7% higher load. The steel yielding for the finite element SCC450 beam model occurs at a load of 204.13 kN, having a displacement of 9.06 mm in Y-direction. The ultimate deflection of the finite element SCC450 model is 39 mm, which occurs at a load of 235 kN. These results have shown that the experimental beam and FEA control beam ultimate loads were the same and a difference of 2.5% in ultimate deflection is noted.

Case 4.5.3: FEA control SCC beam model with SCC450 NS2%

Figure 4-7: Mid-span Load deflection plot for FEA control beam and SCC450 NS2%

In Figure 4.7, the first cracking load for SCC450 NS2% occurs at a load of 29 kN, which is a higher load than the calibrated model by 15%. Curve trends of the FEA SCC and SCC450NS2% beams showed a similar pattern in response with flexure. The steel yielding of the finite element SCC450 NS2% beam occurs at 202 kN with a displacement of 8.07 mm. The mid-span ultimate deflection of the finite
element SCC450 NS2% beam model is 32.3 mm, which occurs at a load of 235 kN. Observations made from mid-span load deflection curves have shown that the FEA SCC450 NS2% has more load bearing capacity and less deflection when compared to the calibrated model by 3% and 18%.

Case 4.5.4: FEA control SCC beam model with SCC450 SF 10%.

Figure 4-8: Mid-span Load deflection plot for FEA control beam and SCC450 SF 10%

In Figure 4.8, the finite element analysis results of mid-span load deflection curves are plotted. In these curves, the first cracking load of SCC occurs at 25 kN and SCC450 SF 10% at 28 kN, which is a high load by 12%. After post cracking of concrete, the FEA SCC beam has less stiffness compared to SCC450 SF 10% model. The steel yielding of finite element SCC450 SF10% beam occurs at 198 kN with a displacement of 7.38mm in the vertical direction. Their observation of the steel yielding for both finite element models show a similar pattern. The ultimate deflection of the finite element SCC450SF10% is 34 mm, which occurs at a load of 235 kN.
In Figure 4.9, load-deflection plots of the self-compacting concrete (SCC450) with a mixture of 10% silica fume and 2% nano silica, and FEA SCC beam was compared. Analyzing curves, the first cracking load of SCC occurs at 25 kN and SCC450 SF10%NS2% at 31.6 kN, which is a higher load by 21%. After the post cracking of concrete, the FEA SCC beam has a less stiffness than the SCC450 SF10%NS2% model. The steel yielding of finite element SCC450 SF10%NS2% occurred at a load of 196 kN, with a 7.08mm displacement in the Y-direction. The ultimate deflection of the finite element SCC450 SF10%NS2% is 31.7 mm occurred at a load of 235.32 kN. Their observations have shown that the SCC450 SF10%NS2% beam having a higher ultimate load than the control SCC beam by 3%, and had a difference of 28% in ultimate deflection.
4.7 Analysis of the results

The Finite element analysis of the F.E control beam applied with different admixtures properties shows linear behavior. After the first crack of validated experimental, the beam with nano silica and silica fumes shows higher stiffness than the experimental beam. These beams also have shown higher ultimate load bearing capacities by 2-4% and less deflection values in the vertical direction compared to the F.E.A of experimental data by 8%-16%.

<table>
<thead>
<tr>
<th>ID</th>
<th>Cracking load (kN)</th>
<th>Deflection at cracking (mm)</th>
<th>Ultimate Load (kN)</th>
<th>Ultimate deflection at mid-span (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>experimental SCC</td>
<td>23.96</td>
<td>1.231</td>
<td>233</td>
<td>42</td>
</tr>
<tr>
<td>SCC validated</td>
<td>24.36</td>
<td>1.3</td>
<td>230</td>
<td>39</td>
</tr>
<tr>
<td>SCC450</td>
<td>28</td>
<td>1.39</td>
<td>235</td>
<td>39</td>
</tr>
<tr>
<td>SCC450 sf10%</td>
<td>28</td>
<td>1.33</td>
<td>235</td>
<td>32.3</td>
</tr>
<tr>
<td>SCC450 ns2%</td>
<td>29</td>
<td>1.26</td>
<td>235</td>
<td>34</td>
</tr>
<tr>
<td>SCC450 sf10%ns2%</td>
<td>31.6</td>
<td>1.37</td>
<td>235</td>
<td>31.7</td>
</tr>
</tbody>
</table>

The linear solution results for the load deflection curves in figure 4.10, obtained from the experimental plots and finite element models of high strength SCC beam shown the similar behavior in the pre-cracking elastic stage, pre-yield and yielding stages by 13%-48%.

In this finite element analysis, the first cracking load of SCCs is having higher loads in the model by 7%-23%. After the post cracking of concrete, the F.E validated SCC beam has a lesser stiffness than the SCC models with nano silica and silica fumes by 4%-11%. Their observation of the steel yielding for both finite element models show a similar pattern. The ultimate deflection of the finite element validated SCC model and SCC450 with different properties is a higher load by 2%-6%.
Figure 4-10: Mid-span load deflection plots for F.E high strength SCC beam with various admixtures
Chapter 5

Conclusions

In this study, the behavior of normal strength reinforced concrete and high strength self-compacting concrete beams under pure flexural loading was investigated. Non-linear finite element analysis (FEA) software program ANSYS was used to model these beams. The FEA models of a reinforced concrete beam, and a SCC beam were validated with existing experimental results in the literature to predict cracks, steel yielding, cracking patterns, and flexural behavior. Additionally, different cementitious material properties, such as compressive strength, modulus of elasticity, splitting and flexural strengths and the effect of plasticizers have been evaluated thoroughly. Finally, the results of FEA models of RC beams using various cementitious materials and, high strength SCC beams with nano silica and silica fumes were compared to control beams. The following conclusions can be drawn:

1. The results of generated finite element analysis models of normal and high strengths RC beams were in good agreement with experimental results of two beams in the existing literature.

2. All the beams using various cementitious materials were having a similar value of cracking loads and shear strengths compared to the normal strength concrete beam. The high strength concrete showed 100% higher first cracking load as compared to the normal strength RC beam.
3. The beam, with concrete mixtures of 25% fly ash and 50 and 100% recycled concrete aggregates, and normal strength self-compacting concrete could provide similar ultimate load and displacement capacities as the control beam.

4. The RC beam with high strength concrete showed a higher gain in load capacity and lower displacement was observed at the mid-span due to additional stiffness.

5. The high strength self-compacting concrete materials did not influence the ultimate load carrying capacities, as failure mode was due to the yielding of steel bars.

6. For the high strength SCC beam, under approximately the same ultimate load level, the deflection at mid-span was lowest when silica nano powder and silica fumes were combined.

5.1 Future work

The present thesis research has provided with the validation of finite element results with experimental data to ensure appropriate modeling parameters were considered and useful for further studies. Though in this research finite element modeling of RC beam with various types of cementitious material properties was performed, the results are constrained due to availability of techniques.

Few cementitious materials were studied and analyzed in this FEA modeling. Developing more sustainable and green materials, and also retrofitted with fiber reinforced polymers (FRP), which will improve the flexural strength than what has been done in this study.
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Appendix A

FEA modeling techniques of RC beam

A.1 Element Types

Preprocessor $\rightarrow$ Element type $\rightarrow$ Add/Edit/Delete $\rightarrow$ solid65. Similarly, we select: Beam $\rightarrow$ Beam188 element is used for modeling steel bars and stirrups.

Also, the solid45 element is selected and used for modeling the steel plates.
A.2 Materials Models

We define the material models for the selected elements.

Material Property → Material Models for 3 elements are defined.
A.3 Modeling Sections

The whole beam is modeled in this thesis. In modeling select: sections → Beam → common sections → Name for section → dimensions of the section are given.

Now volumes of the beam are created: modeling → create→ By Dimensions.

After creating concrete block we assign nodes to concrete block. After assigning nodes we create steel bars and stirrups through the nodes.
A.4 Meshing

Meshing of volumes done. Meshing → volumes → mapped meshing

For accurate non-linear solution, the modeled volume is divided into small rectangular or square shapes.
A.5 Boundary Conditions

We apply loads in the form of pressure on areas of steel plates.

Pre-processor → Loads → Apply → Structural → Pressure → on selected Areas by picking
A.6 Analysis Type

We assign solution controls and their criteria.

Solution → New Analysis → static → Solution controls → basic → no. of steps and sub-steps → Non-linear → set convergence criteria
A.7 Post Processing/Results Viewer

After the convergence of solution, results are plotted.

General Post Processor → results viewer → plot results