ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

PERFORMANCE OF SELF COMPACTING CONCRETE USED IN CONGESTED REINFORCEMENT STRUCTURAL ELEMENT

A Thesis in Structural Engineering

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A Thesis

Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Civil Engineering

The undersigned have examined the thesis entitled '***Performance of Self Compacting Concrete used in congested reinforcement structural element***' presented by **Asnake Kefelegn**, a candidate for the degree of **Master of Science** and hereby certify that it is worthy of acceptance.

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UNDERTAKING

I certify that research work titled “***Performance of Self Compacting Concrete used in congested reinforcement structural element***” is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged/referred.

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ABSTRACT

Self-Compacting Concrete (SCC) is a concrete which can be placed under its own weight without vibration. Whereas Vibrated Concrete (VC) is a concrete which is compacted by means of mechanical vibration. SCC exceeds the current limitations of VC in providing superior material properties, namely passing ability through dense reinforcement resulting in fewer material defects and increasing durability. SCC can be considered as a feasible option where limitations of VC in relation to achieving full compaction of congested reinforcement structural elements.

This paper compares the structural performance of congested reinforcement beams cast with Self Compacting Concrete (SCC) and identical beams cast with Vibrated Concrete (VC). Two different geometric cross-section and length, different longitudinal reinforcement ratios, and same stirrup configuration for all specimens were used.

A total of 12 beams: 6 were tested in the experimental investigation (4 were cast with SCC and 2 were cast with VC in reinforced sections) and 6 (3 for each type of concrete) were investigated using software simulation. The results were compared with design performance prediction as per Euro code2. All beam specimens were tested under monotonic mid-span concentrated loading to determine the overall structural behavior of reinforced concrete beams.

The test results on reinforced beams showed that SCC concrete performed better in reinforcement congested beam element than the referenced VC concrete beam element. The study also showed that the difference in mix composition of SCC from that of VC concrete would have no effects on the overall load-deflection response of reinforced concrete (RC) beam.

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CHAPTER 1 INTRODUCTION

1.1 Background

Self-Compacting Concrete (SCC) can be placed under its own weight without vibration. In addition, it is cohesive enough to be handled without segregation and bleeding. SCC has an improvement over current applications of Super Flowable Concrete (SFC). It exceeds the current limitations of VC and SFC in providing superior material properties, namely passing ability through dense reinforcement, segregation resistance, bleeding and drying shrinkage, resulting in fewer material defects and increasing durability. SCC can be considered as a feasible option where limitations of VC in relation to achieving full compaction of highly reinforced structural elements.

Unlike Japan, USA, and Europe, there has been a reluctance to employ SCC technologies in the Africa construction industry. The Ethiopian construction industry has developed a culture of being particularly slow to adopt and resistant to accept change for its own reasons. This culture has hindered the commercialization of technologies such as SCC.

Modification of the mix design of SCC can have a significant influence on the material’s mechanical properties. Therefore, it is important to investigate whether all of the current design assumptions about Vibrated Concrete (VC) structures are also valid for SCC structures.

1.2 Statement of the problem

Concrete casting in heavily reinforced structural sections, such as those in columns, beams, and beam column joints in moment-resisting frames in seismic areas and in some repair sections, makes the placement of concrete quite difficult. Since Self-Compacting Concrete (SCC) is able to flow and consolidate on its own weight with little or no segregation, it is the best way of tackling such problem.

As SCC concrete’s mix composition is different from’s VC concrete especially for low and normal strength of concrete, it is expected that the structural response of an element would vary. This research will also investigate the effect of mix composition difference on the structural behavior of congested reinforced structural concrete element.

1.3 Objective of the research

The objectives of this research are as follows:

- To investigate the performance of SCC concrete used in congested reinforcement beam element through observing the cracking pattern, load deflection response, ultimate load carrying capacity, and failure modes.
- Comparing the research results with theoretical analysis result as per Euro code2(EC2).

1.4 Scope of the research

In this research, only reinforced slender beams cast with SCC and VC concrete subjected to transverse short-term monotonic load will be investigated. The effect of creep and shrinkage, deep beams, beam-column joint, pre-stressed beams and beams made of high-strength concrete will not be covered in this document.

1.5 Methodology

The overall process of this research includes literature review about properties and structural performance of Self Compacting Concrete, data collection by conducting experimental program, software simulation and theoretical analysis using Eurocode2. Finally, the comparative performance of SCC with respect to VC will be drawn.

1.6 Layout of the research

This thesis is presented in five Chapters and appendix. Chapter 2 of this thesis provides a review of advantages and limitations, fresh properties, Engineering properties of SCC and previous studies on the structural performance of SCC and review on the performance prediction of RC members as per EC2.

Chapter 3 discusses the experimental procedure and setups completed at the Construction Materials Laboratory. In this chapter specimen properties, material properties, and procedures used for experimental data collection is shown.

Chapters 4 is about showing and evaluating of results from the experiment, theoretical analysis, and finite element modeling analysis.

Chapter 5 summarizes the conclusions drawn from the investigation of this study and recommendations for future research are made.

Finally, Appendix describes the gradation of aggregates used, Mechanical properties of used bar, mix design used, fresh properties of investigated SCC concrete, the summary of strength (compressive and splitting tensile strength) and load deflection response of excluded beams from main body.

CHAPTER 2 LITERATURE REVIEW

This chapter reviews the literature on advantage and disadvantage of self-compacting concrete, fresh property tests for self-compacting concrete, previous studies on the Mechanical and structural performance of self-compacting concrete (SCC), and Flexural capacity and deflection of reinforced concrete (RC) members as per Euro code 2.

2.1 Advantages of SCC

Compared to conventional Vibrated Concrete (VC), Self-Compacting Concrete (SCC) achieves higher quality in the construction process by relying far less on the skill of workers for adequate compaction. In overcoming the need for external mechanical compaction of freshly placed concrete, the potential for durability defects resulting from inadequate compaction are significantly reduced. The material allows for improved compaction over VC independent of workmanship, achieving a more uniform, dense and consistent concrete structure and ultimately resulting in a more durable product. When designed and placed correctly, SCC offers advantages in the areas of material properties, product quality, financial costs and associated labor.

Naik et al. (2012) as cited by [1] describes other advantages of SCC over VC as follows:

- Saves the cost of machinery, energy, and labor related to the consolidation of concrete by eliminating it during concrete placement.
- Productivity increases by reducing casting times, which usually leads to a decrease in machinery and personnel cost, thus resulting in total execution times reduced by up to 20-30%.
- High-level of quality control due to more sensitivity SCC to the moisture content of ingredients and compatibility of chemical admixtures.
- High-quality finish, which is critical in architectural concrete, precast construction, as well as for cast-in-place concrete construction.
- Reduces the need for surface defects repairing.
- The increase of the service life of the molds/formwork.

- Industrialized production of concrete.
- Ensuring better quality of cover for reinforcement bars.
- Improves the quality, durability, and reliability of concrete structures due to better compaction and homogeneity of concrete.
- Easily placed in thin-walled elements or elements with limited access.
- Improves working environment at construction sites by reducing noise pollution especially at precast concrete products plants.
- Eliminates the need for hearing protection.
- Provides an opportunity for using high-volume of by-product materials such as fly ash, quarry fines, blast furnace slag, limestone dust, and other similar fine mineral materials.

The above-mentioned advantages are a direct result of the properties of SCC, namely the flowing ability, passing ability and resistance to segregation.

2.2 Disadvantages of SCC

SCC has substantial dissimilarities in production in comparison to VC due to the sensitivity to variations in quality and consistency of mix constituents. SCC's sensitivity to variation requires a high degree of accuracy in batching which subsequently relies on comprehensive testing to ensure the batching is consistent. The batching itself may need additional additives when it is compared to VC such as super-plasticizers, Viscosity Modifying Admixtures (VMAs) and higher powder contents. As SCC requires higher powder contents, lower water to cement ratio and additional chemical admixtures compared to VC, increase in the raw material cost of the concrete, makes it more expensive**.** This additional cost, as well as the necessary testing, has limited the use of SCC to only specialized applications where VC will not provide the specified level of quality. SCC also requires a higher quality for the formworks of placing because, due to its fluidity, there is a possibility of formwork spillage or cracking as a result of the higher pressure exerted. Moreover, there is lack of evidence and knowledge of the long-term behavior and durability of SCC due to the nature of new technology. There is also a reluctance to utilize SCC in a commercial application as there was a lack of guidance, principles and effective test methods.

As the mix design used in SCC is highly sensitive to variation, it is crucial that selections of materials are rigorously tested and precise measurements and monitoring of each batch are methodically assessed. VC can cope with variations by adjusting the amount of mechanical compaction whereas SCC requires alterations to the proportions of fine aggregates, coarse aggregates, cement, powder, water, and admixtures [1]. Although there are restrictions with SCC, they are outweighed by its many advantages and the development of technologies associated with SCC has enabled the limitations to be gradually reduced. It is anticipated that most limitations will be overcome with continual advances and this will ultimately lead to the transition from it being a special concrete to a standard concrete.

2.3 Fresh properties of SCC concrete

Key fresh flow properties that characterize a concrete mix as self-compacting include [2];

1. Filling/flowing ability/fluidity

May be described as the ability of the SCC to flow through and completely fill the gaps of a formwork without the need for mechanic consolidation. In order to achieve a good filling capacity, concrete must fulfill the following properties.

i. Low friction among the particles

In order to obtain concrete with as highly deformability as possible, Aggregate-aggregate friction must be brought to the lowest level by limiting the direct contact between particles. In order to achieve this, the distance between particles must be increased by reducing the amount of coarse aggregate or by increasing the amount of paste in the mixture. In order to reduce friction between the powder-type particles of the additions increasing the water content within the paste is not recommended. Using a high quantity of water may lead to concrete segregation, thus generating the possibility of obtaining concrete with low hardened performances both from a resistance and durability perspective.

ii. High deformability paste

If we want to obtain concrete with an adequate self-compaction reducing the friction between its content solid particles is not enough. Paste itself needs to have a good deformability. As a consequence, in order to obtain concrete capable of overcoming various obstacles and reaching a good filling capacity, it is important to ensure a good flow capacity and an adequate segregation resistance. This is attainable by adding superplasticizers which can increase deformability without decreasing the cohesion among particles. Nevertheless, we must take into account the fact that using superplasticizers for large quantities combined with a low water/powder ratio can negatively affect mixture behavior because concrete will tend to have a higher deformability but with a lower flow rate. In general, to obtain a concrete with a good filling capacity the following action would be taken.

Action	Procedure
Reduction of friction among particles	• The content of coarse aggregate must be as low as possible which implies a high content of the paste • Optimal content of addition relative to the aggregates and the cement used
Increasing paste deformability	• Superplasticizers • Optimal water/powder ratio

Table 2-1 Requirements to note in order to achieve an adequate filling ability

2. Passing ability

The ability to pass through congested reinforcement whilst resisting segregation, separation or blocking. SCC may be considered with good deformability only when it simultaneously meets the requirements concerning the filling and passing abilities. For a concrete with a good filling capacity and segregation resistance, blockages will appear in the following conditions:

- ➢ The maximum size of the aggregate is too high
- ➢ The content of coarse aggregate is too high

To have an adequate flow rate and passing ability we must take into account the aspects detailed in the following table.

Action	Procedure
The increase of cohesion between materials to reduce segregation	• Low water/powder ratio • Use of viscosity admixtures
Compatibility between free space and aggregate sizes	• Low volume of coarse aggregate • Limiting the maximum size of aggregates used

Table 2-2 Requirements to follow in order to achieve an adequate passing ability

3. Stability/resistance to segregation

It is the ability to remain homogeneous during the mixing and placing processes. There are two types of segregation, both are extremely important for self-compacting concrete.

a. Dynamic segregation: it refers to concrete components resistance to the separation during casting of concrete in formwork. An adequate dynamic stability is necessary for SCC at the time when the shape of the formwork elements implies passing through narrow spaces.

b. Static segregation: it refers to the concrete resistance against the free water flow (bleeding), segregation or sedimentation from the surface while concrete is still in the plastic phase, if this feature is not taken into account, great variations of the mechanical properties can occur for the elements produced by using this concrete.

During placing, self-compacting concrete can have multiple segregation forms such as flow of free water i.e. physically or chemically unbound of water, Segregation between paste and aggregates, and blockage tendency for coarse aggregates. In order to avoid flow of free water, the decrease of free water from within the mixture is essential. This can be attained through several procedures such as the optimization of the water/powder ratio or the use of additions with a greater absorption surface. Use of lower water/powders ratio may be considered as practical in order to increase concrete segregation resistance. Sometimes, depending on the application specifications, viscosity modifying admixtures (VMA) may be used to achieve an adequate segregation resistance.

Finally, to achieve an adequate segregation resistance the following measures have to be taken:

Action	Procedure
Reducing the separation between solids	• Limiting the coarse aggregate content • Reducing the aggregates size • Low water/powder ratio • Viscosity admixture
Minimizing free water flow (bleeding)	• Low water content • Low water/powder ratio • Viscosity admixture • High surface additions

Table 2-3 Requirements to consider in order to achieve an adequate segregation resistance.

All of the three properties stated above are necessary to obtain in the end a superior quality concrete, which fulfills all the design requirements.

2.4 Testing Fresh Properties of SCC

At the stage before solidification, self-compacting concrete is required to have three qualities: high-flowability, resistance against segregation and passing ability. Therefore, it is important to test whether the concrete is self-compactable or not and the test result would be used for estimating proper mix proportioning. The common tests currently used, although not standardized, for assessment of fresh SCC, are described here.

2.4.1 Slump Flow Test

A standard Abram’s slump cone of VC is filled in direction shown in figure 2.1. with the SCC mix and not compacted. The consistency of SCC is evaluated with the slump-flow test, which consists of determining the mean spread of the concrete at the base of the slump test after the end of spreading. Such value can be related to the yield stress of the concrete, and the rate of spread with time can be related to the plastic viscosity. The slump-flow test is used to assess filling ability, or the unrestricted deformability of SCC [3]. Concrete mixes with slump-flows greater than 800mm are expected to segregate and slump-flows less than 650 mm are considered to have insufficient passing ability [4]. The Slump-flow testing apparatus is shown in figure 2.1 [4].

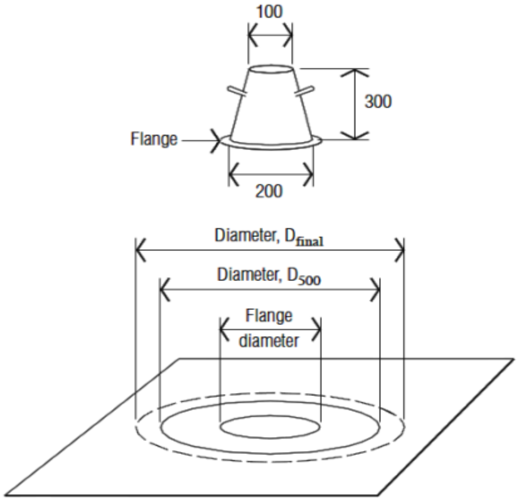


Figure 2-1 Slump-flow test equipment

2.4.2 V-Flow Test

The V-Flow test involves measuring the time taken for a completely filled V-Flow funnel test apparatus (Figure 2.2) to empty once opened. This test is used to evaluate the flowing ability of the SCC and can assess the dynamic stability of the concrete. Concrete is generally considered to be self-compacting with a V-Flow time of 6 seconds or more. A long flow-out duration can be due to segregation (aggregates stacking at the opening) or excessive concrete viscosity [3].

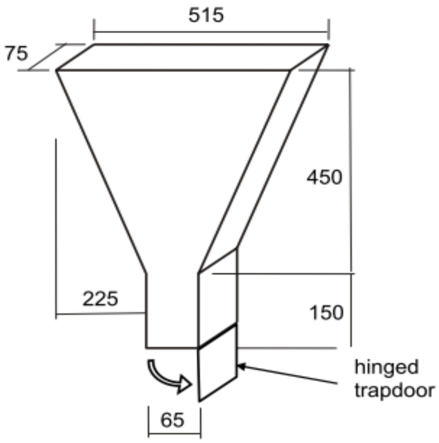


Figure 2-2 V-funnel test equipment (rectangular section) [5]

2.4.3 L-Box Test

The L-Box test evaluates the filling and passing ability through parallel bars with constant spacing without segregation or blockage, as shown in Figure 2.3. SCC with relatively low dynamic segregation resistance or high viscosity and relatively low filling ability will have limited flow through this highly restricted section. SCC with a filling capacity greater than 80% can be expected to fill congested formwork [5].

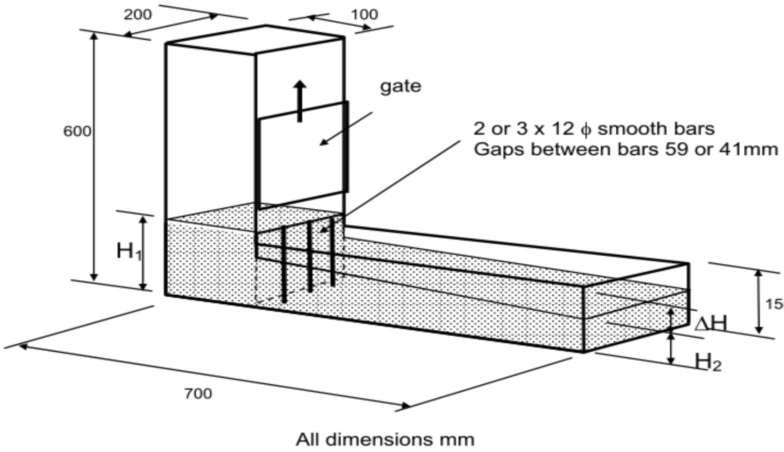


Figure 2-3 L-box test equipment [5]

2.5 Acceptance Criteria for SCC concrete

For high fluidity concrete, the acceptance criteria of self-compactablity should be determined considering the shape, dimensions and bar arrangement for the structure in which concrete is placed.

Three ranks of self compactability are defined as follows [6]:

Rank 1: Self-compatability for high-fluidity concrete placed into members having complicated shapes and small cross sectional areas with a minimum clearance of 35 to 60mm between reinforcing bars.

Rank 2: Self-compatability for high-fluidity concrete placed into reinforced concrete structures or members with a minimum clearance of 60 to 200mm between reinforcing bars.

Rank 3: Self-compatability for high-fluidity concrete placed into structures having large cross-sectional areas, with little or no reinforcement, such as structures where the minimum clearance between reinforcing bars exceeds 200mm or plain concrete structures. As per [6] the acceptance criteria for fresh properties of powder type SCC is shown in table below.

Rank of self-compactability		1	2	3
Fluidity	Slump flow(mm)	600-700	600-700	500-650
Resistance to segregation	Funnel flow time of V_{75}funnel(s)	9-20	7-13	4-11
	500mm flow time(s)	5-20	3-15	3-15
Filling (mm)	U-box	Over 300(R1)	Over 300(R2)	Over 300(without restriction)

Table 2-4 Tests for SCC fresh properties and Acceptance criteria for powder type SCC concrete of different ranks [6]

Test name	Property To measure	Units	ACI	EFNARC	European research project"Testing SCC"
Slump flow	Filling	mm	450-760	600-800	600-750
T500 slump flow	Filling	Sec	2-5	2-7	3.5-6
V-funnel	Filling	Sec	-	6-12	3-12
L-box	Passing	H_2/H_1	0.8-1.0	0.8-1.0	0.7-1.0
U-box	Passing	(H_2-H_1)	-	0-30	-

Table 2-5 Tests for SCC fresh properties and the criteria values set by different institutions

In common, we can summarize the testing method and properties observed as below [2].

Used Method	Observed properties
Abrhams Cone	➢ Filling ability - fluidity ➢ Segregation resistance - viscosity
V Funnel	➢ Filling ability – fluidity
L Box	➢ Passing ability - rate of blockage ➢ Filling ability

Table 2-6 Testing methods and properties observed

Where:

EFNARC is European Federation of Specialist Construction Chemicals and Concrete Systems

ACI is American Concrete Institute

2.6 Mechanical properties of SCC

Researchers have observed a distinct engineering property difference between the two types of concrete. This difference is especially evident when the proportions of coarse aggregate (size and shape) or paste content of SCC mixtures are different from those of VC [7]. Mechanical properties such Compressive strength, Tensile strength, and Modulus of elasticity reviewed from different reference is summarized below.

2.6.1 Compressive Strength

SCC will typically have a slightly higher compressive strength when compared to a conventional concrete of similar water to cement (W/C) ratio. This is due to the improved interface between the aggregate and the hardened paste [5].

2.6.2 Tensile Strength (Axial)

For a given concrete strength and maturity, the tensile strength can normally be assumed to be the same as conventional concrete. This is due to the fact that the paste volume has no significant impact on tensile strength [5]. However, from [7] SCC mixtures with limestone filler or fly ash, W/C (water to cement ratio) = 0.45 to 0.61 and C/P (Cement to Powder ratio) = 0.5 to 0.6 indicates that the conversion factor A_{sp} to correlate the splitting tensile strength is slightly lower (0.84±0.004) than the values proposed by EC2(A_{sp}=0.9). Thus, when determining $f_{ct,m}$ by means of splitting tensile strength results and based on previously mentioned codes, an overestimation of the tensile strength is obtained. The conversion factor for bending (A_{sfl} = 0.59±0.1) was also significantly lower than the 0.69 prescribed in EC2 [7].

2.6.3 Modulus of Elasticity

The modulus of elasticity is often the controlling parameter in slab design and post-tensioned concrete elements. Since the bulk of the concrete is aggregate, the aggregate modulus of elasticity has the most impact on this value. However, the increased volume of paste and the decreasing amount of coarse aggregate in SCC can decrease this value slightly [5].

The best fit line for the modulus of elasticity of VC data is very close to that of the approximate relationship given in EC2, but the Modulus of Elasticity for the SCC mixes is on average about 40% lower than those of the VC mixes at low strength levels, with the difference reducing to less than 5% at high strengths. This behavior is consistent with the lower course aggregate quantities in SCC [8].

The influence of the W/CM (water to cementitious ratio) on the modulus of elasticity was found to be comparable to that observed on the compressive strength. The difference between SCC and VC in the modulus of elasticity is greater for lower compressive strength [7].

2.7 Structural behaviors of SCC concrete

In this section, a summary of the available research studies about structural behavior of reinforced SCC is presented. Researchers have observed a distinct difference between the two types of concrete in engineering properties. This difference is especially evident when the proportions of coarse aggregate (size and shape) or paste content of SCC mixtures are different from those of VC. Various engineering properties such as flexural strength, ductility and seismic consideration, and cracking behavior for structural members cast with SCC mixture will be discussed.

2.7.1 Flexural strength

The flexural resistance of SCC beams, like that of VC beams, mainly depends on the W/C ratio, Supplementary Cementitious Material (SCM), coarse aggregate size and volume, and the quality of the interface between the aggregate and cement paste. Using SCM with low W/C ratio improves the concrete microstructure, increases the density and strength of the matrix, and hence increases flexural strength. The coarse aggregate also plays a significant role in flexural strength. Increasing coarse aggregate content appears to result in a reduction in flexural strength for a given aggregate size. This may be explained by the interface transition zone around the aggregate, which is potentially weaker in tension than mortar or aggregate. With more aggregate added into concrete mixtures, more interfaces are formed in the hardened concrete and more reduction of flexural strength occurs. From experimental observation, a reduction up to 22 % in flexural strength was observed by increasing the aggregate content from 36 to 44 % [7].

SCC is usually developed by increasing the fines content at the expense of coarse aggregate content. It is characterized by dense, less permeable structure due to the low W/C ratio and the use of SCM. In addition, the maximum size of coarse aggregate in SCC is usually small to facilitate the concrete flowability. Therefore, the flexural strength of SCC may be higher than that of VC with similar mixture proportions.

Yasser Sharifi performed an investigation on the flexural performance of SCC concrete. Six simply supported reinforced SCC beams were tested under four-point bending with a pure moment region. All beams were designed for the shear span to depth ratio of 3.5. The final conclusion of the research was experimental ultimate moments were found to be higher by about (0-7)% and (0-8)% compared to the ultimate moment predicted based on ACI and CSA (Canadian Standards Association) code, respectively. [9]

2.7.2 Cracked Behavior

Sonebi et al. [10] investigated the flexural behavior of concrete beams (200 mm width x 300 mm depth x 3800 mm length) cast with SCC, VC, and reinforced SCC (SCC60, RC60, and FSCC60 respectively) with standard cylindrical compressive strengths of 60MPa. The SCC mixture contained extra SCM (slag), lower W/C ratio and less coarse aggregate than the VC mixture. The results of their investigation showed that at service load, more and slightly wider cracks with greater penetration is occurred in VC beams than in SCC beams.

Luo and Zheng [11]investigated the cracking loads, flexural capacities and failure modes of reinforced SCC beams and compared the results with VC beams. Based on the research the crack moment of the SCC beams was slightly lower than VC beams.

De Corte and Boel [12]studied the flexural resistance and cracking of reinforced SCC/VC beams with varying reinforcement ratios. The SCC and VC mixtures had a comparable compressive strength and the nominal maximum size of the coarse aggregates for both mixtures was 16 mm. Six reinforced concrete beams measuring 2400 mm in length, 150 mm in width, and 200 mm in depth were tested under static and dynamic tests. The beams were simply supported with a span length of 2000 mm and a two-point load device was used to transfer the applied load. The maximum failure loads for VC and SCC showed excellent agreement with less than 5% difference. The crack width evolution in SCC beams was somewhat slower compared to VC beams.

Cuenca et al. [13] investigated the cracking behavior of reinforced SCC/VC beams subject to shear load. The SCC and VC shared the same raw materials and had similar cylindrical compressive strength (50 MPa); the SCC mixture was characterized by a smaller amount of gravel, compensated by cement and sand. Three reinforced I concrete beams, measuring 6000 mm in length, 500 mm in width, and 700 mm in depth were cast and tested; during flexural tests, shear cracks opening was measured by means of an optical technique and results show that both SCC/VC mixes provided for very similar results irrespective of the higher content of fines of SCC.

2.7.3 Ductility

Ductility is the ability of concrete to sustain significant inelastic deformation prior to failure. It is a desirable structural property as it allows absorption of energy for impact load in case of earthquake, dynamic impact or explosion, and provides warning before structural failure.

SCC is expected to have better ductility than VC mixture due to better particle gradation, fewer voids, and a denser matrix structure [14]. In the seismic design of reinforced concrete members, it is necessary to allow for relatively large ductility. Therefore, members constructed with SCC are expected to have similar or even better seismic behavior than those constructed with VC.

Lin et al. [14] compared the ductility of SCC columns with that of VC columns. The SCC and VC mixtures in their study had approximately the same amount of coarse aggregate, but the SCC contained more SCM and less water content than the VC. Their results indicated that the descending range of the stress-strain curve of SCC columns exhibited better ductility than VC columns. Also, the load dropped

2.8 Flexural capacity of RC members as per Euro code 2

The flexural ultimate moments (M_u) for singly reinforced section can be predicted based on EC2 code provisions. The ultimate flexural resistance and yielding flexural resistance (the moment at the onset of yielding of tension reinforcement) of a concrete beam is calculated using the laws of statics by summing the moment about an axis through the point of application of compressive force (C) or tension force (T) (Figure 3.5). The equations used to predict theoretical flexural cracking moment (M_{cr}) and ultimate flexural moment capacity ($M_{u,}$) are put below.

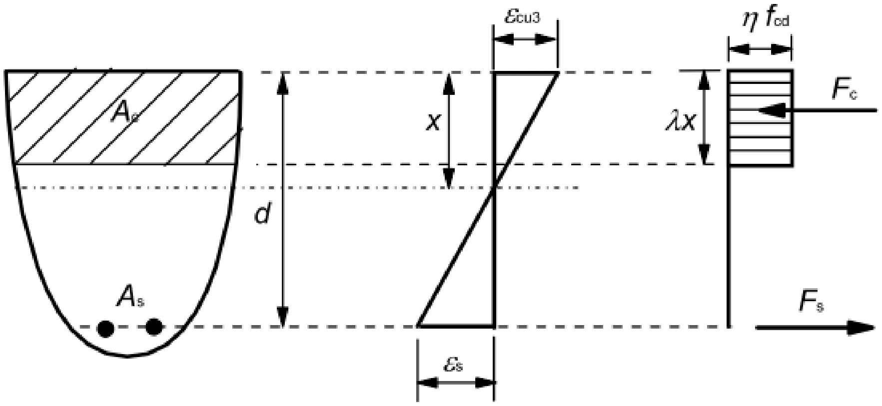


Figure 2-4 Rectangular stress distribution

$\eta = 1.0$ and $\lambda = 0.8$ for $f_{ck} \leq 50\ MPa$

$$M_u = A_s . f_{yd} . \left(d - 0.4x\right) = 0.8x . b . f_{cd} \left(d - 0.4x\right) \quad \text{……...……………………..........2-1}$$

$$x = \frac{A_s . f_{yd}}{(0.8 . b . f_{cd})} \quad \text{……..…………………………..………………………………..…..….. 2-2}$$

$$f_{cd} = \frac{f_{ck}}{\gamma_C} \left(f_{ck} \leq 50\ MPa \right) \text{ and } f_{yd} = \frac{f_{yk}}{\gamma_s} \quad \text{..……....…………….…..….……………………. 2-3}$$

$$f_{ctm,fl} = max \left\{ \left(1{,}6 - \frac{h}{1000} \right) f_{ctm} ;\ f_{ctm} \right\} \quad \text{……………………………………………………...2-4}$$

$$f_{ctm} = 0.3 . f_{ck}^{\ 2/3} \quad \text{……………………………………….….………………………......2-5}$$

$$k_x = \frac{\varepsilon_{cm}}{\varepsilon_{cm} + \varepsilon_y} = \frac{x}{d} \leq 0.448 \text{ for } \varepsilon_y = \frac{f_y}{E_s} \quad \text{……………………………………………………………2-6}$$

Where:

M_u	is the ultimate moment
M_y	is the yielding moment
M_{cr}	is the crack moment
A_s	is the tensile cross-sectional area of reinforcement
f_{yk}	is characteristic yield strength of reinforcement
f_{yd}	is the design yield strength of reinforcement
f_{ck}	is characteristic compressive cylinder strength of concrete at 28 days
f_{cd}	is the design value of concrete compressive strength
Es	is the modulus of elasticity of reinforcing steel = 200GPa
ε_{cm}	is the compressive strain in the concrete
ε_y	is Strain of reinforcement steel at yielding load
β_c	is the resultant compressive force location from the top end
x	is neutral axis depth
d	is the effective depth of a cross-section
I_{un}	is the moment of inertia for un-cracked concrete section
$f_{ctm,fl}$	is the flexural tensile strength
h	is the total member depth in mm
f_{ctm}	is the mean axial tensile strength
y_t	is the neutral axis distance from the extreme tension fiber

CHAPTER 3 MATERIAL, EXPERIMENTAL PROCEDURE AND INSTRUMENTATION

3.1 Introduction

In this chapter, discussion on the materials used, experimental procedure and setups completed at the Construction Materials Laboratory, AAU (Addis Ababa University), AAiT (Addis Ababa Institute of Technology) are presented. This research was completed in three steps. The first step involved the study of the fresh properties of the SCC, the second part consisted of validating the use of SCC for congested reinforcement structural element sections and the third part involves numerical simulation of larger size congested reinforced SCC and VC concrete beam element.

The main variables of the investigated beam specimens were: (i) type of concrete (SCC or VC), (ii) longitudinal reinforcement ratio, (iii) Geometry of the beam. The properties of experimentally investigated beam specimen are shown in figure 3.4**.**

3.2 Materials

3.2.1 Cement

Commercially available Pozollana Portland Cement (PPC) grade 32.5 was used.

3.2.2 Fine Aggregate

The fine aggregate used was obtained from Alage quarry site. The physical properties of fine aggregate obtained from laboratory test result are summarized in table 3-1 below.

Physical properties of Sand	Values
Specific gravity	2.23
Fineness Modulus	3.40
Absorption capacity (%)	6.16
Silt Content (%)	3.8

Table 3-1 Physical properties of used Fine Aggregate

3.2.3 Coarse Aggregate

The coarse aggregate from a local crushing unit having 12.5mm maximum size was used. The physical properties of coarse aggregate obtained from laboratory test result as per ASTM are summarized in table 3-2 below.

Physical properties	Values
Aggregate size(mm)	12.5
Bulk density(kg/m^3)	1511
Specific gravity (Dry basis)	2.86
Fineness modulus	6.44
Absorption capacity (%)	1.49

Table 3-2 Physical properties of used Coarse Aggregate

3.2.4 Super-plasticizer

Naphthalene sulphonate based (SASplast SP60) super-plasticizer conforming to ASTM C-494-Type F and G is used. Properties of Superplasticizer are summarized in table 3-3 below.

Properties	**Observation**
Color	Dark brown liquid.
Specific gravity(kg/liter)	1.22±0.03 at 25˚c
Chemical base	Naphthalene sulphonate
Air Entrainment	1-2% depending on dosage
Chloride Content	Nil

Table 3-3 Properties of used Superplasticizer

3.2.5 Reinforcement Bar

Locally produced steel was used in this study. The Mechanical properties of reinforcing steel obtained from laboratory test result are summarized in Table 3-4 below (see Appendix for more information).

Diameter of bar and lot	Average-yield strength (MPa)	Average-ultimate strength (MPa	Average-ultimate strain (%)
ø 8,$_1$	524.81	619.33	9.33
ø 8,$_2$	439.64	550.12	9.83
ø 12,$_1$	582.59	685.30	30.17
ø 12,$_2$	339.97	495.30	20.16
ø 14	460.32	614.60	12.50

Table 3-4 Mechanical properties of used Reinforcing Steel

The subscript stands for a lot i.e. two different tests were carried out for two lots (Ø 8mm and Ø 12mm bar) which were bought at different times.

3.2.6 Concrete

The specimens were cast in wooden molds using cast in situ concrete. During the casting process, samples of concrete were prepared in 6 cubes with a side length of 150mm and 6 cylinders, with size 100mm diameter and 200mm height or 150mm diameter and 300mm height, depending on the amount of concrete left. Samples were taken for each type of concrete for compressive strength and splitting tensile strength test and 3 of them were tested 7 days after casting, and the rest 3 samples were tested 28 days after casting (See Appendix). In the mix proportions of concrete (detailed mixed design is attached in the appendix part), the target strength was C-35/45.

Mix proportions used for SCC and VC concrete is shown in table 3-5 below (see Appendix for more information).

Concrete Type	SCC	VC
Water(kg/m^3)	190	200
Cement(kg/m^3)	550	442
Maximum aggregate size(mm)	12.5	12.5
Coarse aggregate (kg/m^3)	628.8	854.98
Fine Aggregate (kg/m^3)	789.8	801.51
Super-plasticizer (kg/m^3)	11.55	0

Table 3-5 Final mix composition used for SCC and VC concrete

For Vibrated or Conventional concrete, *ACI absolute volume mix design method* is used. Whereas for SCC concrete, initial trial mix design based on the *European Guidelines for Self-Compacting Concrete* [5], *EFNARC 2002* [4] *and Japan Society of Civil Engineers* [6]was used. From table 3.5 it is observed that the mix composition for preparation of SCC and VC concrete varies. And the variation is significant for coarse aggregate (more than 25% difference).

3.2.6.1 Fresh properties of SCC and VC concrete

Immediately after the completion of mixing, the SCC concrete mixture was tested for fluidity (slump flow), passing ability (L-box) and segregation resistance (V-funnel). Whereas only slump value is used to evaluate the fresh properties of VC concrete. The slump value obtained from test result is 25mm for VC. The summaries of fresh property test results for SCC and VC are put in table 3.6 below.

Figure 3-1 Slump flow test

Figure 3-2 V-funnel test

Figure 3-3 L-box test

Test type	SCC	VC
Slump flow(mm)	700	-
Slump value(mm)	-	25
T50cm slump flow(s)	3.6	-
L Box(H2/H1)	0.89	-
V Funnel(s)	13	-

Table 3-6 Summary of fresh properties of SCC and VC concrete from laboratory test result

SCC concrete is expected to satisfy acceptance criteria for Rank 1 self compactability [6] and SCC concrete satisfies the acceptance criteria for powder type Rank 1 self-compactable concrete. Since U-box is not available in our laboratory, L-box is used to assess the passing ability.

3.2.6.2 Hardened properties of concrete

The compressive strength and splitting tensile strength determination of SCC and VC concrete were carried with cube mold having 150x150x150mm dimension and cylinder having 100x200mm or 150x300mm respectively. The concrete was poured into mold without vibration for SCC and with vibration for about 60sec for VC concrete. The mold was removed after 24 hours for VC and after 2 days for SCC concrete. After removing a mold and moist cured, the strength test result was taken at the 7th and 28th days of casting and the test result is summarized in table 3.7 below.

Concrete type	Sample No.	The compressive strength of cubic size 15cm (MPa)		Cylindrical Splitting tensile strength (MPa)	
		7th day	28th day	7th day	28th day
SCC	1	38.17	47.56	3.45	3.36
	2	41.77	43.61	3.67	3.62
	3	37.95	46.45	2.83	3.60
	Average	**39.30**	**45.87**	**3.31**	**3.53**
VC	1	30.91	36.50	2.34	3.82
	2	24.75	48.49	3.18	3.16
	3	24.92	39.14	2.91	3.33
	Average	**26.86**	**41.38**	**2.81**	**3.44**

Table 3-7 Hardened properties of SCC and VC concrete

As per [15]conformity of concrete compressive strength is assessed on specimens tested at 28 days. Each individual test result, f_{ci}, shall satisfy this equation, $f_{ci} \geq (f_{cu} - 5)$ N/mm^2. Where f_{cu} can be taken for average cubic compressive strength. And the 28 days compressive strength which shown in table 3.7 satisfies this guideline. It also stated that the individual variation should not be more than ±15% of the average as per IS246. For SCC concrete it is acceptable but for VC concrete it is little above 15%. The difference is positive that it is good to accept rather than to reject.

3.3 Specimens

Specimens are designed by considering hose diameter of vibrator and rank1 self compactability [6]. Mostly 60mm diameter vibrator hose is available in the market. Hence, Shear reinforcement is designed with center to center spacing of 60mm so that the hose cannot pass through between bars. Longitudinal reinforcement is designed with clear spacing less than 35mm and double layer of tension reinforcement is used to simulate the congestment of reinforcement.

The experimental performance investigation included total six (6) specimens with 160x200mm cross section varying longitudinal reinforcement ratios (1.32%, 2.04%, 2.98% and 3.33%) made with SCC (f_{Cu} = 45.87 MPa) to all specimen, VC (f_{Cu} = 41.38 MPa) to specimen two (#)2 and (#3) (see figure3.4).

Each beam specimen (figure 3.4) is identified with a label consisting of a series of letters, as presented in Table 3-8. The First two letters SC and VC indicate the concrete type used i.e. SCC and VC. The third letter B indicates beam. The fourth numbers 1, 2, 3, and 4 shows sample number. Summary of beam specimen identification symbol is shown in table below.

Symbol	Stands for	Symbol	Stands for
SCB1	Reinforced SCC concrete beam specimen one		
SCB2	Reinforced SCC concrete beam specimen two	VCB2	Reinforced VC concrete beam specimen two
SCB3	Reinforced SCC concrete beam specimen three	VCB3	Reinforced VC concrete beam specimen three
SCB4	Reinforced SCC concrete beam specimen four		

Table 3-8 Beam specimen identification symbol

The details of the mechanical properties of steel reinforcement used for the experimental tested beam specimens are presented in Table 3.9 below. The number of longitudinal bars and diameter used are shown in figure3-4. A Shear reinforcement diameter 8mm with a spacing of 60mm on centers in specimen one to four was used. The steel properties were obtained from tensile loading tests performed on at least three samples from each lot of reinforcing bars. The yield and ultimate strength of the longitudinal reinforcement bar are shown in the table below. Shear reinforcement used for specimen one up to three has a yield strength of 439.64MPa and ultimate strength of 550.12MPa, and for specimen four it has a yield strength of 524.81MPa and ultimate strength of 619.33MPa. Concrete cover used for all specimen is 25mm.

The provided tension reinforcement ratio is checked and all are below balanced tension reinforcement ratio.

Specimen	Rebar Diameter	Yield strength (MPa)	Area of tension reinforcement (mm^2)	Effective depth(d)	Tension reinforcement ratio (%)	Stirrups and spacing
SCB1	top= 8mm	439.64	339.29	161.00	1.32	Ø8c/c60
	bot =12mm	582.59				
SCB2 and VCB2	top and bot = 8mm	524.81	150.80	150.23	2.04	Ø8c/c60
	bot =12mm	582.59	339.29			
SCB3 and VCB3	top= 8mm	439.64	678.59	142.50	2.98	Ø8c/c60
	bot =12mm	339.97				
SCB4	top =12mm	582.59	769.69	144.40	3.33	Ø8c/c60
	bot =14mm	460.32				

Table 3-9 Details of investigated beam specimens

During casting of the concrete beams, VC was thoroughly vibrated in the forms, while SCC was only poured into forms from the top without any mechanical vibration. Fresh concrete was sampled with standard 150×150x150mm cubes and companion cylinders to determine the splitting tensile strength.

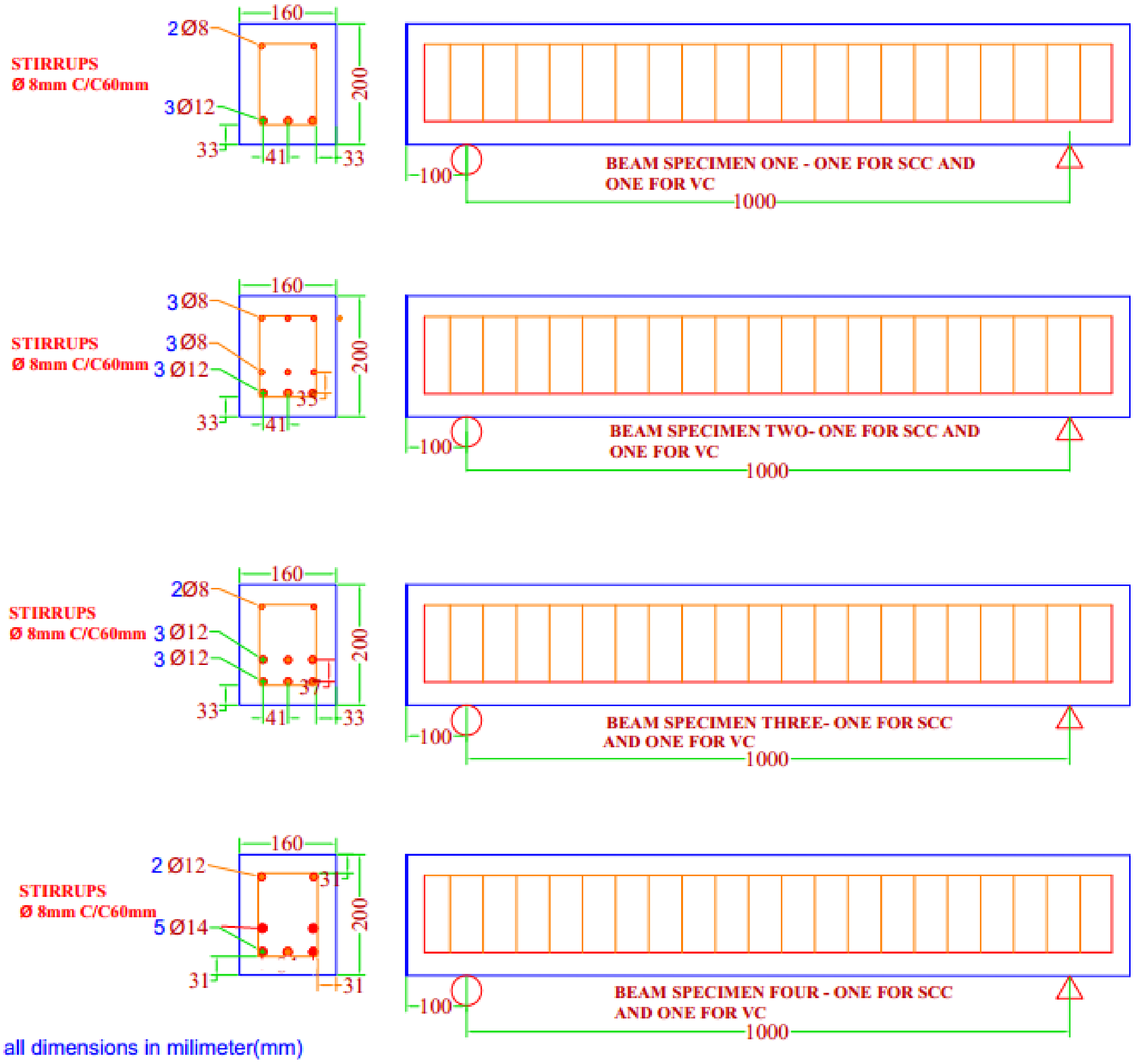


Figure 3-4 Cross-sectional dimensions, number and diameter of longitudinal bars, stirrup spacing, and diameter of beam specimens.

3.3.1 Specimen preparation

Figure 3-5 Specimen preparation, formwork, and steel reinforcement

3.3.2 Instrumentation

The mid-span deflection of beam specimens was measured using 2 LVDTs (Linear Variable Differential Transformers) installed on each side of mid-span of the beam (figure 3.6).

The load was applied using a medium sized hydraulic jack**.** The jack was put on the load cell and it gets the reaction from the rigid steel frame above it. During testing, a data acquisition system recorded the load and longitudinal deformations of the beam specimens at regular intervals. The testing was terminated when the loading system reached its maximum displacement or when the beam specimen was unable to sustain additional loading. All of the instrumentations were connected to a data logger and the experimental data was directly obtained in a USB disk.

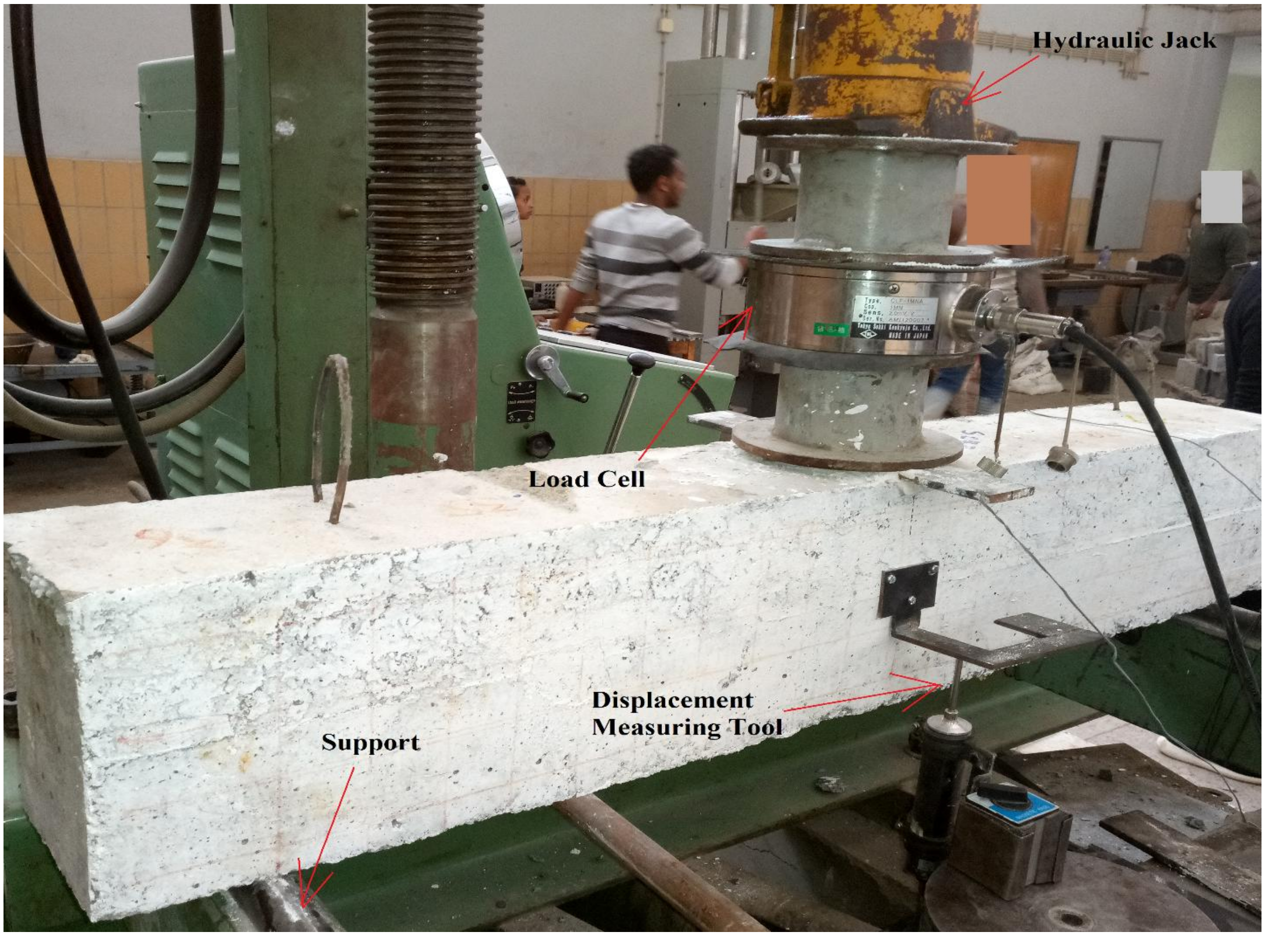


Figure 3-6 Typical beam test setup, SCB3

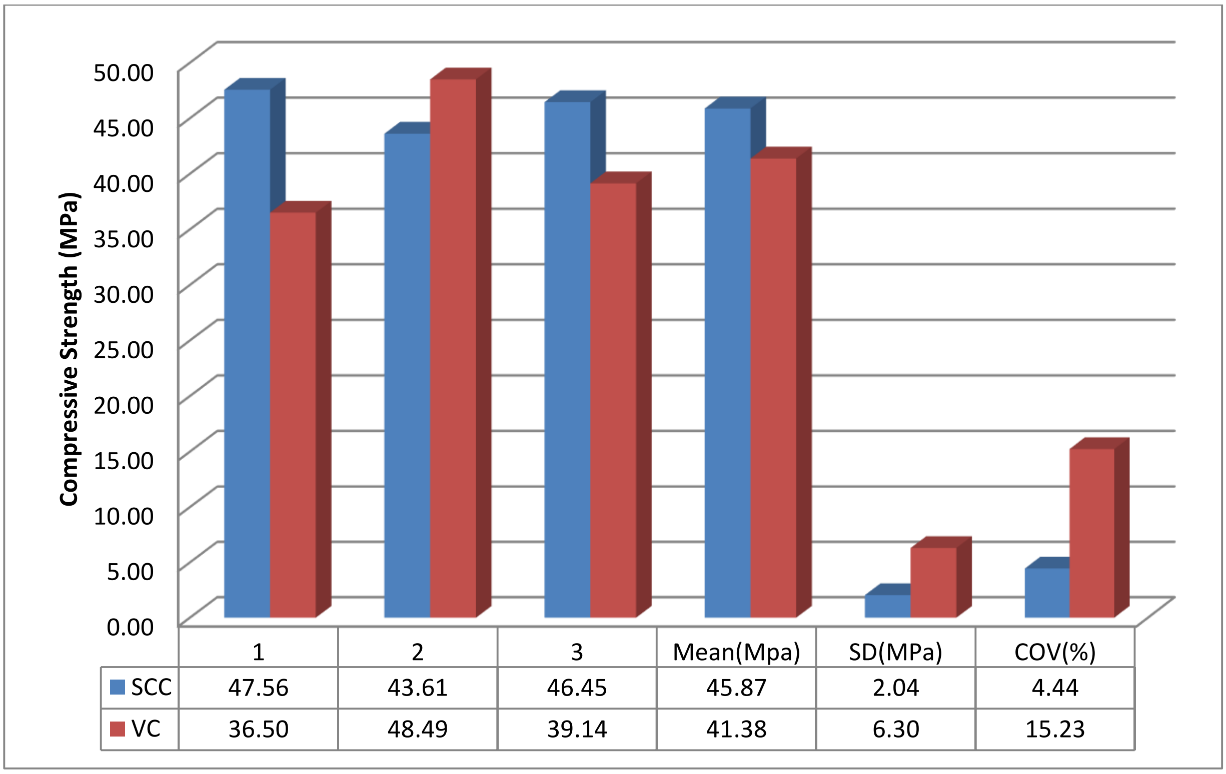
CHAPTER 4 RESULTS AND DISCUSSIONS

In this chapter, results and discussions of variation in compressive strength of Self Compacting Concrete (SCC) and Vibrated Concrete (VC), failure mode and cracking pattern of SCC and VC beam specimens, load-deflection response of reinforced SCC and VC beam specimens, ultimate load carrying capacity and deflection at service load of SCC and VC beam specimens, comparison of experimental and theoretical analysis (EC2) results will be made.

4.1 Results from Experiment

4.1.1 Concrete Compressive Strength Variation Comparison

To investigate the consistency of the concrete compressive strength, the 28 days compressive strength of used SCC and VC concrete is used. The 28 days compressive strength of SCC and VC concrete and the corresponding standard deviation (SD) and coefficient of variance (COV) is shown in figure 4.1.



	1	2	3	Mean(Mpa)	SD(MPa)	COV(%)
🟦 SCC	47.56	43.61	46.45	45.87	2.04	4.44
🟥 VC	36.50	48.49	39.14	41.38	6.30	15.23

Figure 4-1 Compressive strength variation comparison

As shown in figure 4-1, it is observed that the strength distribution for SCC (Standard Deviation (SD) = 2.04 MPa, Coefficient of Variance (COV) = 4.44%) concrete is homogenous than the corresponding VC (SD = 6.30MPa, COV = 15.23) concrete.

Figure 4-2 Typical Coarse aggregate distribution of SCC concrete

From figure 4-2, it is observed that the aggregate distribution of SCC concrete is uniformly dispersed.

4.1.2 Experimentally observed failure mode, crack pattern, and load-deflection response

The flexural failure and crack pattern observed for SCC beam(left) and VC beam (right) is shown in figure below.

Figure 4-3 Flexural failure and crack pattern observed for SCB2(left) and VCB2(right)

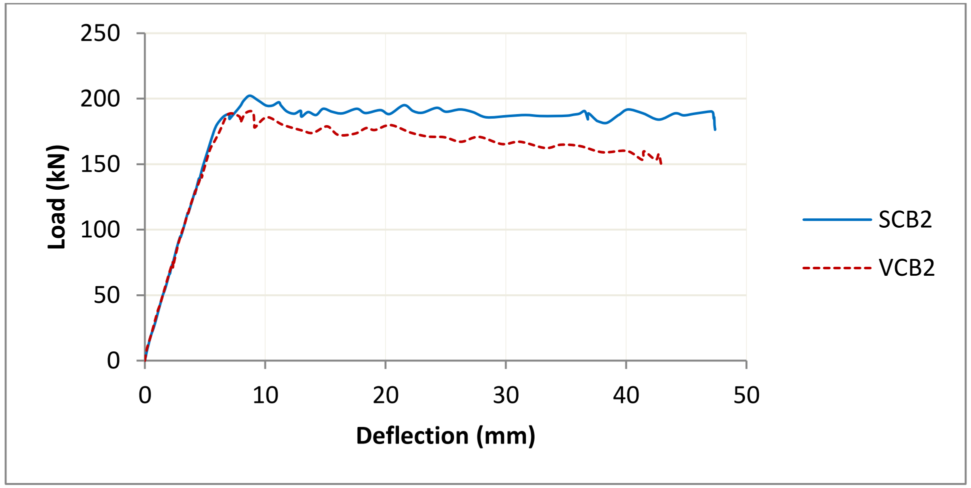


Figure 4-4 Comparison of load -deflection response for beam specimen two

Figure 4-5Flexural failure and crack pattern observed for SCB3(left) and VCB3(right)

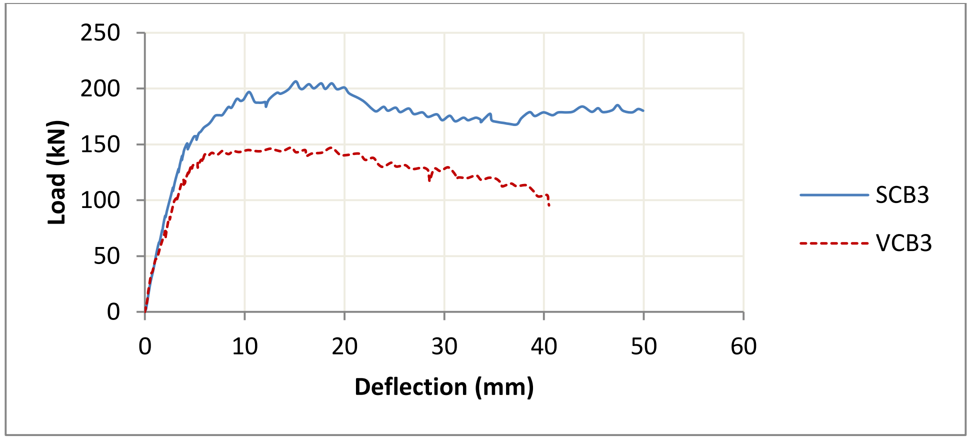


Figure 4-6 Comparison of load -deflection response for beam specimen three

As it was shown in Figure 3-6, Loading, set up to simulate displacement-based loading, was applied using a medium sized hydraulic jack. The jack was placed on the load cell and it gets the reaction from the rigid steel frame above it. Deflection measuring tools were attached to the beam at the mid-span. Load and deflection data were recorded by the Data Logger and taken by USB (flash disc). The data obtained was plotted on MS excel sheet.

During conducting of test on 2 reinforced VC beams and 4 SCC beams, it was observed that all failure was dominated by flexural and the crack pattern formed are similar in nature. Initially, the hairline cracks were formed. Then the increment of load caused the cracks to expand further to vertical and then it propagates from the bottom tension zone to the top compression zone. Loading was stopped when concrete in compression zone crashed and during failure the load sustaining capacity of SCB beam was better than VCB beam. In the course of concrete in compression zone crashes concrete crashing sounds were witnessed for VCB and Not any sounds were witnessed for SCB. It is also shown in in figure 4.3 that the crack formation pattern of reinforced SCC and VC beam is similar.

Deflections were measured along the mid-span of the beam at every load stages. The Load - deflection comparison of reinforced SCC concrete beam specimen and referenced VC beam specimen is shown in Figure above. From Figure 4.4, it is observed that the deflection at L/2 in SCC beams were similar with VC beams before yielding load. This shows that mix composition difference for production of SCC and VC concrete has no effect on Load-deflection response of the investigated beam specimen. From the above graph, it is understood that the maximum load sustaining capacity of SCC beam specimen is better than the referenced VC beam specimen. And the ultimate load carrying capacity of SCB2 and SCB3 beam specimen are, by about 6.6% and 40.3% respectively, greater than referenced VC beam. This is maybe as a result of better compaction, homogeneity of SCC concrete, a smaller amount of coarse aggregate, and denser cement matrix. Reducing the course aggregate quantity, in fact, leads to an increase of the strain at peak load and to an increase of the flexural strength. But, the difference is exaggerated for SCB3. This happened as a result of unfortunate 20mm increment in the depth during casting of SCB3 beam.

The load-deflection and crack pattern observed for SCC concrete beam specimens (SCB1 and SCB4) are put on appendix.

From the observed experimental result, it is concluded that SCC concrete performed better than the referenced VC concrete in reinforcement congested structural beam element.

4.2 Finite Element Analysis Using VecTor2

4.2.1 Introduction

The experimental procedure is mostly preferred as it provides real-life structural behavior that can be guaranteed of high accuracy. However, the need to execute the experimental study is very expensive and time-consuming. Besides, there are some other real-life situations that do not demand experimental work. Hence, numerical model is more preferred option as it allows to reduce the number of physical prototypes and experiments. In this section NLFEA (Non-Linear Finite Element Analysis) of the additional six beams other than those experimentally tested beams which are large in cross section and length: three for SCC and three for VC reinforced beam is discussed. Since the experimental investigation was limited to six small cross section and short in length beams, additional beams which are greater in cross section and length are investigated using simulation. This is will add further information on performance of SCC concrete used in congested reinforcement structural beam. Before conducting numerical analysis of such beams, the modeling analysis is validated using experimentally obtained data in section 4.1.2.

For NLFEA software called VecTor2 is used. The VecTor© is nonlinear finite element analysis (NLFEA) programs developed at the University of Toronto to analyze different types of structures such as beams (VecTor1), 2D membrane structures (VecTor2), 3D solid structures (VecTor3), plates and shells (VecTor4), plane frames (VecTor5), and axisymmetric solids (VecTor6). This program developed by researchers studying on reinforced concrete behavior and applications of the finite element method over the last two and half decades.

The VecTor2 element library includes a three-node constant strain triangle, a four-node plane stress rectangular element and a four-node quadrilateral element for modeling concrete with smeared reinforcement; a two-node truss-bar for modeling discrete reinforcement; and a two-node link and a four-node contact element for modeling bond-slip mechanisms.

In this modeling, it is decided to model the beam with four node rectangular elements for the concrete, and two node truss bar elements for the longitudinal reinforcing bars. Two reinforced concrete material types are utilized. One type represents the plain concrete cover. The other type models the web region of the beam with one smeared reinforcement component, which represents the stirrup reinforcement.

4.2.2 Material Properties Modelling

VecTor2 utilizes non-linear functions of stress and strain regarding the constitutive relationships. This approach is amenable to concrete given that the combined behavior of aggregates, cement, and reinforcement which that can often only be described by empirical relationships.

The following discussion describes the constitutive and behavioral models pertaining to the response of the reinforced concrete material. [16]

4.2.2.1 Models for Concrete Materials

4.2.2.1.1 Modelling Vibrated Concrete (VC)

1. **Compression Pre-Peak Response**

The Hognestad parabola, is a simple compression response curve, suitable for normal concrete strengths (f_c'<40 MPa) is used. The stress-strain curve is described by the following relationship:

$$f_{ci} = -f_p\{2(\frac{\varepsilon_{ci}}{\varepsilon_p}) - (\frac{\varepsilon_{ci}}{\varepsilon_p})^2\} < 0 \; for \, \varepsilon_{ci} < 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{4-1}$$

The stress-strain relationship is symmetric about ε_p, diminishing to zero stress at zero strain and $2\varepsilon p$. Note that the Hognestad parabola predefines the initial tangent stiffness, E_c, as follows:

$$E_c = 2 f_p / \varepsilon_p \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{4-2}$$

2. **Compression Post-Peak Response**

Park, Priestly and Gill (1982) modified a stress-strain curve proposed by Kent and Park to account for the enhancement of concrete strength and ductility due to confinement. The linearly descending branch of the modified stress-strain curve is liberally adapted for VecTor2 as follows:

$$f_{ci}^{b} = -[f_p + Z_m f_p(\varepsilon_{ci} - \varepsilon_p)] < 0 or -0.2 f_p for \varepsilon_{ci} < \varepsilon_p < 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4\text{-}3$$

Where: $Z_m = \dfrac{0.5}{\dfrac{3+0.29|fc'|}{145|fc'|-1000}.(\dfrac{\varepsilon_o}{-0.002}) + (\dfrac{|f_{lat}|}{170})^{0.9} + \varepsilon_o}$ (f_c' and f_{lat} in MPa) ……………4-4

and *flat*, is a summation of principal stresses, acting transversely to the direction under consideration:

$$f_{lat} = f_{c1} + f_{c2} + f_{c3} - f_{ci} \leq 0 \text{ i=1} or \ 2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4\text{-}5$$

4.2.2.1.2 Modeling Self-Compacting Concrete (SCC)

The pre-peak and post-peak concrete response of SCC concrete is modeled as VC. The main difference between two concretes is in terms of tension stiffening and crack stress calculation constitutive relationships.

Tension stiffening model used for SCC concrete was Lee 2010 stress-strain response. Whereas for VC, Modified Bentz 2003 was used (see [16] for more).

4.2.2.2 Modeling Ductile Steel Reinforcement Bar

The constitutive and behavioral models pertaining to the response of reinforcement materials under monotonic stress-strain response of reinforcement is discussed.

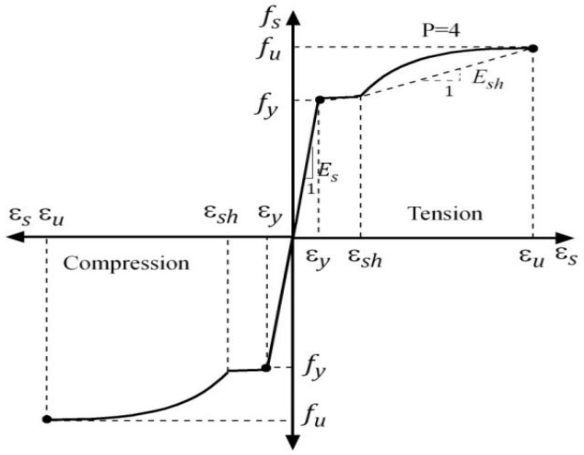


Figure 4-7 Ductile steel reinforcement stress-strain response, Nonlinear strain-hardening

The reinforcement stress, *fs*, in tension and compression is determined as follows:

$$f_s = \begin{cases} E_s \varepsilon_s & for\, \varepsilon_s \le \varepsilon_y \\ f_y & for\, \varepsilon_y < \varepsilon_s \le \varepsilon_{sh} \\ f_u + \left(f_y - f_u\right)\left(\dfrac{\varepsilon_u - \varepsilon_s}{\varepsilon_u - \varepsilon_{sh}}\right)^4 & for\, \varepsilon_{sh} < \varepsilon_s \le \varepsilon_u \\ 0 & for\, \varepsilon_u < \varepsilon_s \end{cases}$$

………………………………………………….. 4-6

where ε_s is the reinforcement strain ($\varepsilon_s=|\varepsilon_s|$), ε_y is the yield strain, ε_{sh} is the strain at the onset of the strain hardening, ε_u is the ultimate strain, E_s is the elastic modulus, f_y is the yield strength, f_u is the ultimate strength. The strain hardening modulus, Esh is defined as below:

$$E_{sh} = \frac{\left(f_u - f_y\right)}{\left(\varepsilon_u - \varepsilon_{sh}\right)} \qquad \text{……………………………………………………………………} \quad 4\text{-}7$$

In general, the summary of constitutive relationship used in modeling is shown in table below

Analysis techniques		**SCC**	**VC**
1	Convergence Criteria	Displacements - Weighted Average	Displacements - Weighted Average
2	Analysis Mode	Static Nonlinear- Load Step	Static Nonlinear- Load Step
Concrete Modelling		**SCC**	**VC**
1	Compression Base Curve	Hognestad(Parabola)	Hognestad(Parabola)
2	Compression Post-Peak	Modified Park-Kent	Modified Park-Kent
3	Compression Softening	Vecchio 1992-A	Vecchio 1992-A
4	Tension Stiffening	**Lee 2010 (w/ Post-Yield)**	**Modified Bentz 2003**
5	Tension Softening	Nonlinear (Hordijk)	Nonlinear (Hordijk)
6	Confinement Strength	Montoya/Ottosen	Montoya/Ottosen
7	Concrete Dilatation	Montoya w/Limit-Iso	Montoya w/Limit-Iso
8	Cracking Criterion	Mohr-Coulomb (Stress)	Mohr-Coulomb (Stress)
9	Crack Stress Calculation	**Advanced (Lee 2010)**	**Basic (DSFM/MCFT)**
11	Concrete Bond	Gan-Vechio Model	Gan-Vechio Model
Bar modeling		**SCC**	**VC**
1	Stress-strain response	Nonlinear strain-hardening	Nonlinear strain-hardening
2	Dowel action	Tassios Model (crack slip)	Tassios Model (crack slip)
3	Buckling	Akkaya 2013 (Modified Dhakal-Maekawa)	Akkaya 2013 (Modified Dhakal-Maekawa)

Table 4-1 Summary of constitutive relationships and analysis parameters used for modeling using VecTor2

4.2.3 Verification of Modeling Results

The following cross-section properties is used in simulation verification of reinforced SCC and VC concrete beams. For verification purpose, SCB2 and VCB2 are selected and experimental and simulation result are compared as shown in figure 4.10 and 4.11 respectively. All dimensions are put in millimeter(mm).

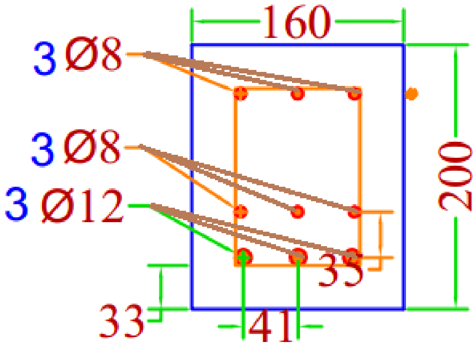


Figure 4-8 Cross-sectional properties of SCB2 and VCB2 specimen used in verification.

The details of the mechanical properties of steel reinforcement used for the beam specimens are presented in Table 3.9. The number of longitudinal bars and diameters used are shown in figure 4.12 and figure 3.4. A Shear reinforcement diameter 8mm with a spacing of 60mm on centers in specimen one to four was used. The yield and ultimate strength of diameter (∅) =8mm longitudinal reinforcement bar are 524.81MPa and 619.33MPa respectively. The yield and ultimate strength of ∅=12mm longitudinal reinforcement bar are 582.59MPa and 685.30MPa respectively. The yield and ultimate strength of shear reinforcement bar are 439.64MPa and 550.12MPa respectively. Concrete cover used is 25mm.

The automatic mesh generation facility with the hybrid discretization type was used to create the mesh shown in Figure 4.9 below. Each layer of longitudinal reinforcing bars was entered as a separate reinforcement path with its corresponding material type. The node at the support is restrained from displacements in the longitudinal and transverse direction at left support and transverse direction at right support.

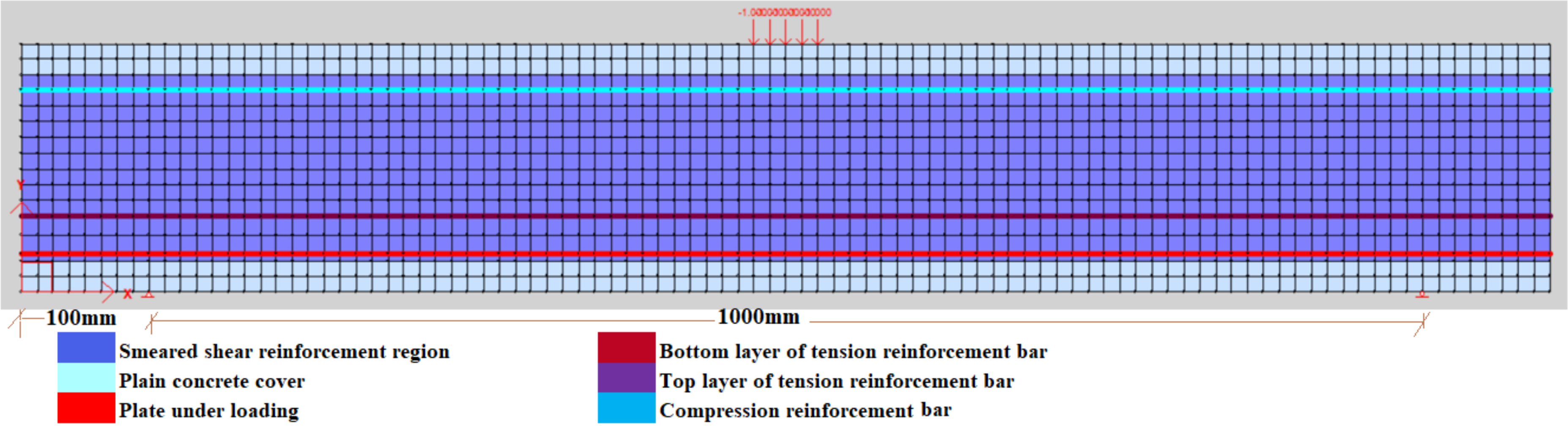


Figure 4-9 Finite element mesh for an SCB2 and VCB2 beam with thickness, T=160mm

One load case was utilized to impose a support displacement of 1 mm at the mid-span. The load factor was increased monotonically from zero to failure in increments of 1mm. The analysis parameters used for SCC concrete beam and VC concrete beam model is shown in section 4.2. The self-weight of the beam is not included. For validation purpose, experimental data from SCB2 and VCB2 is used.

The thickness of the SCB2 and VCB2 specimen is 160mm. Modulus of Elasticity of steel (Es) = 200000MPa is used. The tensile strength, f't, Cylinder Strain ε_o and initial tangent modulus of elasticity of the concrete, Ec, was calculated by a formula recommended in the manual [16]. Cylinder Compressive Strength, f'_c, can be taken equivalent to f_{ck} defined in EC2. Poisson's ratio value for reinforced concrete material equal to 0.2 was used for all specimens.

4.2.3.1 Simulation Result and verification for SCC beam

The figure below shows the comparison of experimental result with NLFEA software simulation result for SCB2.

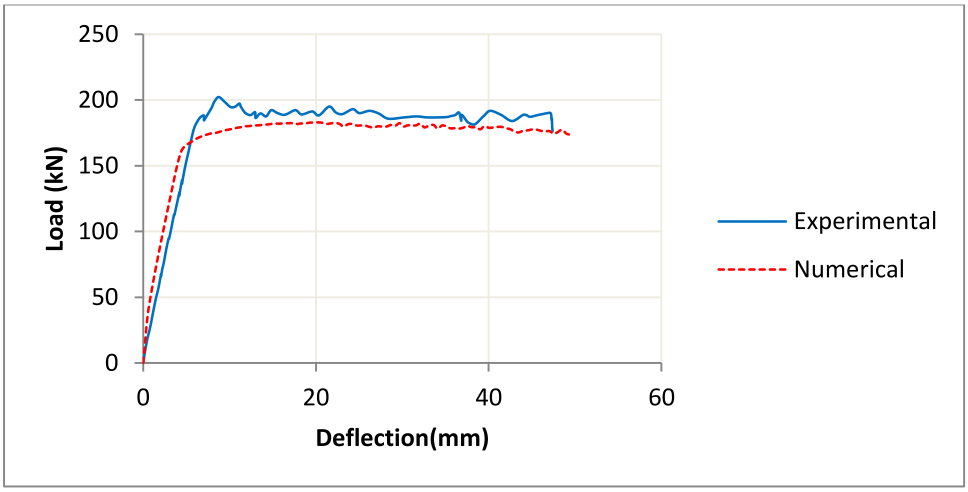


Figure 4-10 Verification of simulation for reinforced SCC concrete beam

From the result, it is observed that load-deflection response simulation of reinforced SCC beam is more or less fit with experimentally obtained load-deflection response result. Ultimate load also be predicted with relative error of {(202.33-182.92)/202.33*100% =9.6%} difference.

4.2.3.2 Simulation Result and verification for VC beam

The Figure below shows the comparison of experimental result with NLFEA software simulation result for VCB2.

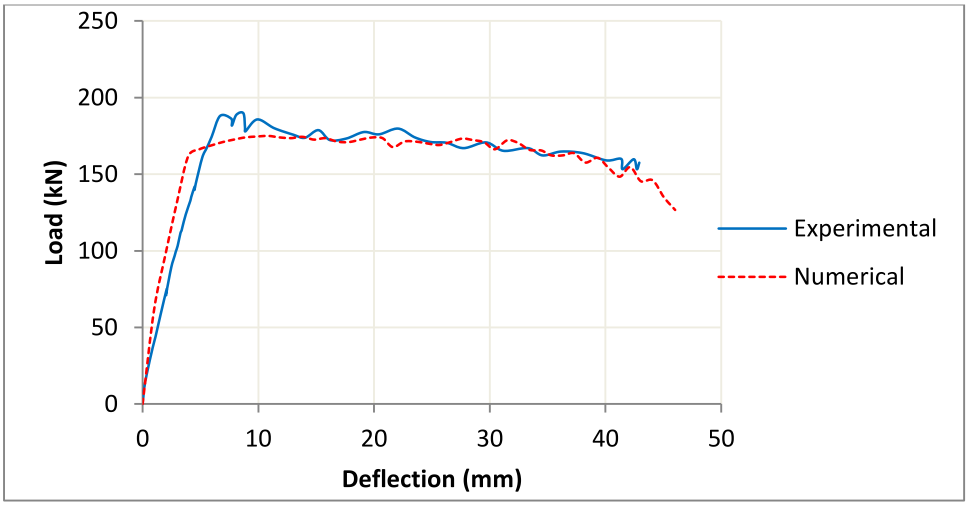


Figure 4-11Verification of simulation for reinforced VC concrete beam

From results, it is observed that load-deflection response simulation of reinforced VC beam is more or less fit with experimentally obtained load-deflection response result. Ultimate load also be predicted with relative error of {(189.83-174.92)/189.83*100% =7.85%} difference.

4.2.4 Specimens

Since the experimental investigation was limited to six small cross sectionals and short in length specimens, additional beam specimens which are greater in cross section and length are investigated using simulation. This is will add further information on performance of SCC concrete used in congested reinforcement structural beam. The extra 6 (3 for each types of concrete) beam specimens, with cross section properties shown in figure 4.12, are used for additional investigation. The spacing between tension reinforcing bar is 25mm for specimen five and six, and 30mm for specimen seven (see figure 4.12). Each beam specimen (figure 4.13) is identified with a label consisting of a series of letters, as presented in Table 4-2. The First two letters, SC and VC indicate, the concrete type used i.e. SCC and VC. The third letter B indicates beam. The fourth numbers 5, 6, and 7 shows sample number. Summary of beam specimen identification symbol is shown in table 4.2 below.

Symbol	Stands for	Symbol	Stands for
SCB5	Reinforced SCC concrete beam specimen five	VCB5	Reinforced VC concrete beam specimen five
SCB6	Reinforced SCC concrete beam specimen six	VCB6	Reinforced VC concrete beam specimen six
SCB7	Reinforced SCC concrete beam specimen seven	VCB7	Reinforced VC concrete beam specimen seven

Table 4-2 Additional beam specimen identification symbol

Two-dimensional nonlinear finite element analyses were carried out for total six specimens (3 for SCC and 3 for VC beam specimens). In simulation equal compressive strength of SCC and VC concrete is used. The concrete compressive strength used is 36.7MPa, maximum aggregate size used is 12.5mm and other cross-sectional properties of specimens, which varies with tension reinforcement ratio, are shown in the table 4.3 and figure 4.12 below.

Specimen Identification	Rebar diameter	Bar yield strength (MPa)	Area of tension reinforcement (mm^2)	Effective depth(d)	Tension reinforcement ratio (%)	Stirrup diameter and spacing
SCB5 and VCB5	top and bottom12	339.97	2375.05	420.00	1.88	Ø12c/c70
SCB6 and VCB6	top and bottom 12	339.97	3166.73	401.50	2.63	Ø12c/c70
SCB7 and VCB7	top 12	339.97	3694.52	397.50	3.10	Ø14c/c70
	bottom14	460.32				

Table 4-3 Details of additional beam specimens

The thickness for B5, B6, and B7 specimens is 300mm. Modulus of Elasticity of steel (Es) = 200000MPa is used. The tensile strength, f't, Cylinder Strain εo and initial tangent modulus of elasticity of the concrete, Ec, was calculated by a formula recommended in manual [16]. Cylinder Compressive Strength, f'c, can be taken equivalent to f_{ck} defined in EC2. Poisson's ratio value for reinforced concrete material equal to 0.2 was used for all specimens. Concrete cover used is 25mm.

The provided tension reinforcement ratio is checked and all are below balanced tension reinforcement ratio.

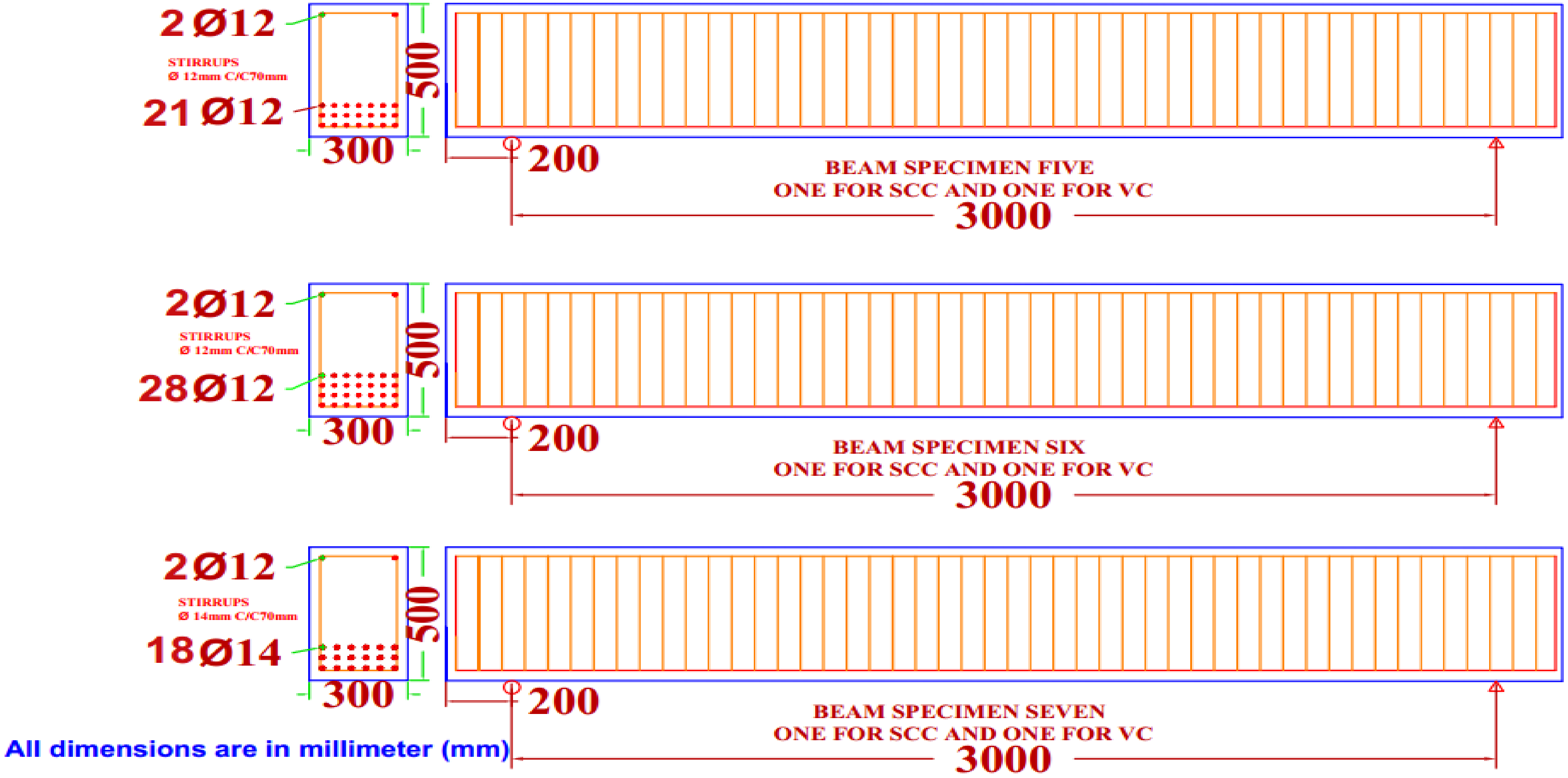


Figure 4-12 Specimen five, six, and seven cross-sectional dimensions, length, number and diameter of longitudinal bars, stirrup spacing and diameter.

4.3 Comparison of load-deflection results of the additional SCC and VC reinforced beams.

In this section comparison of load-deflection response of reinforced SCC beams (SCB5, SCB6, and SCB7 and reinforced VC beams (VCB5, VCB6, and VCB7) will be made. Deflections are the mid-span deflection of the beam at every load stages. The Load - deflection relation-ship of reinforced SCC concrete beam specimen and referenced VC beam specimen is shown in Figure 4.13, 4.14, and 4.15 below.

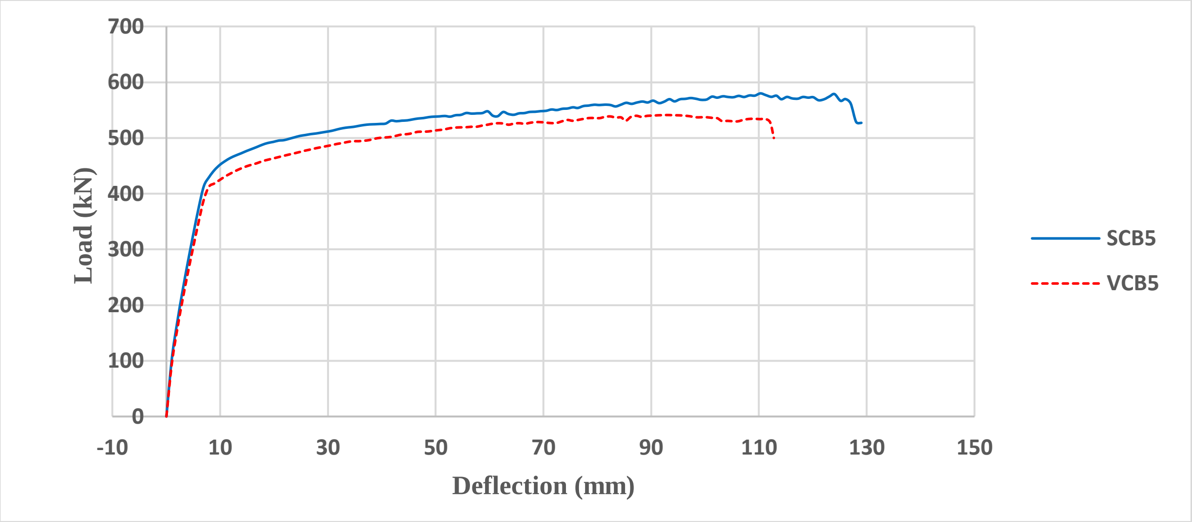


Figure 4-13 Comparison of load -deflection response of SCB5 and VCB5

As shown in the above graph, it is understood that the maximum load sustaining capacity of SCC beam specimen is better than the referenced VC beam specimen. The ultimate load carrying capacity of SCC beam specimen is also greater by about 7% than referenced VC beam. In experiment the load sustaining capacity of referenced VC beam is expected to be lower as simulation considers homogenous compressive strength distribution.

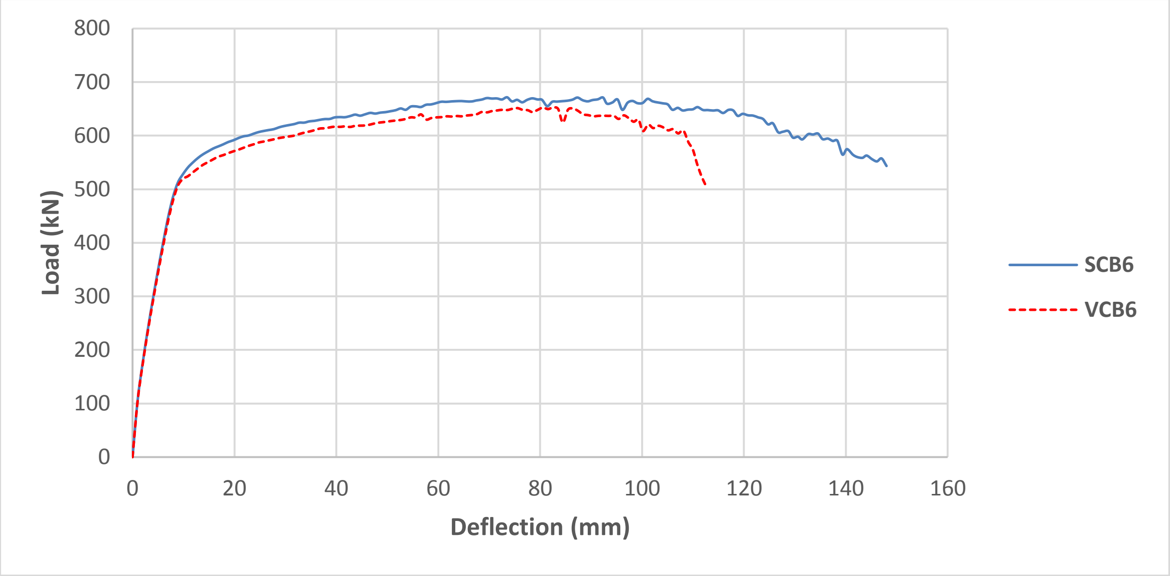


Figure 4-14 Comparison of load -deflection response of SCB6 and VCB6

From the above graph, it is understood that load sustaining capacity of SCC beam specimen is better than the referenced VC beam specimen. The ultimate load carrying capacity of SCC beam specimen is also greater by about 3% than referenced VC beam. In experiment the load sustaining capacity of referenced VC beam is expected to be lower as simulation considers homogenous compressive strength distribution.

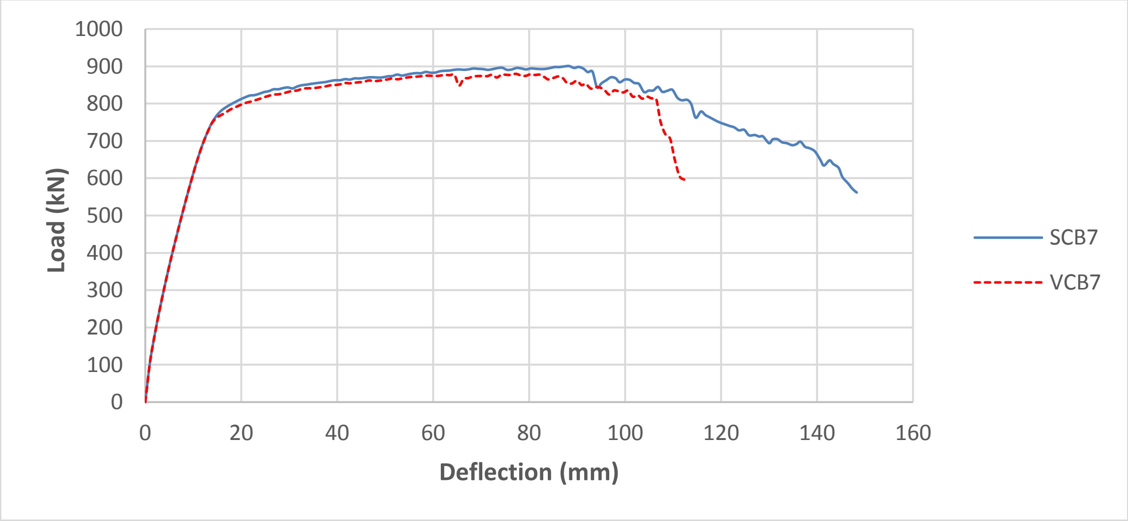


Figure 4-15 Comparison of load -deflection response of SCB7 and VCB7

From the above graph, it is understood that load sustaining capacity of SCC beam specimen is better than the referenced VC beam specimen. The ultimate load carrying capacity of SCC beam specimen is also greater by about 2.4% than referenced VC beam. it is also observed that the ultimate load carrying capacity of reinforced SCC concrete beam and reinforced VC concrete beam gets closer to each other.

In general, from simulation result, it can be understood that load carrying capacity of SCC beam is relatively better than the referenced VC beam. And the load sustaining capacity of SCC beam is also better than the referenced VC beam specimen. From the results, it is understood that the difference becomes lower as the tension reinforcement ratio increases.

4.4 Comparison of Eurocode2 results with experimental results

Here in our country, for design purpose the capacity of structural members is predicted as per Euro code 2. This section shows how the experimentally obtained results interrelated to the theoretically obtained results, and the results are summarized in the table below. Design equations used in Eurocodes2 of practice for predicting the flexural strength of reinforced concrete slender beams was discussed in section 2.8**.** The following tables show the summary of empirical ultimate moment resistance and experimental ultimate moment resistance

Beam Identification symbol	Ultimate Moment capacity, EC2, (kNm)	Ultimate Moment capacity, Actual(kNm)	Ultimate moment ratio (Actual/EC2)
SCB1	25.27	42.46	1.68
SCB2	30.87	50.58	1.64
SCB3	29.06	51.58	1.77
SCB4	32.35	57.09	1.76
SCB5	260.77	435.37	1.67
SCB6	315.20	503.58	1.60
SCB7	436.39	675.51	1.55
VCB2	30.07	47.46	1.58
VCB3	24.49	36.77	1.50
VCB5	260.77	405.97	1.56
VCB6	315.20	489.67	1.55
VCB7	436.39	659.97	1.51

Table 4-4 Summary of Relative Performance of SCC and VC beam specimens

From Summary table 4.4 it is understood that the ultimate load carrying capacity of SCC beam is relatively better than corresponding VC beam. From a design point of view, the experimentally obtained ultimate load results are far safer. i.e. on average 1.67 times of the design load for SCC beam and 1.54 times of the design load for VC beam.

CHAPTER 5 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Based on the experimental investigation and numerical simulation results, the following conclusion are drawn:

1. SCC concrete performed better than the referenced VC concrete in reinforcement congested structural beam element.
2. The mix composition difference for making SCC and VC concrete has no significant effect on load-deflection response of beam before yielding.
3. In the process of failure under vertical load, SCC concrete beams sustain loads for a longer time than VC concrete beams. And also, sounds were heard during VC concrete beams failure.
4. There is no obvious cracking pattern difference was observed between SCC and VC concrete.
5. SCC concrete has less compressive strength variation than corresponding VC concrete.
6. The experimental ultimate moments of SCC beams were found to be higher by about (55-77) % and the experimental ultimate moments of VC beams were found to be higher by about (50-58) % compared to the ultimate moment predicted based on EC2.

From this research it is also observed that:

7. The fresh properties of SCC are highly sensitive to little variation.

5.2 Recommendation

The following recommendations are proposed for further research.

An experimental program could be conducted on SCC to study;

1. Performance of SCC concrete used in highly congested beam-column joint structural element.
2. Structural performance of slab under different strength of SCC concrete.
3. The crack size and behavior of structural members under different loading types.
4. The reversed cyclic and repeated loading effects in the short-term and long-term behavior of the structural members.
5. Shear capacity of structural element without shear reinforcement.

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APPENDIX

A-1 Gradation of fine aggregate (FA) and coarse aggregate (CA) as per ASTM C33

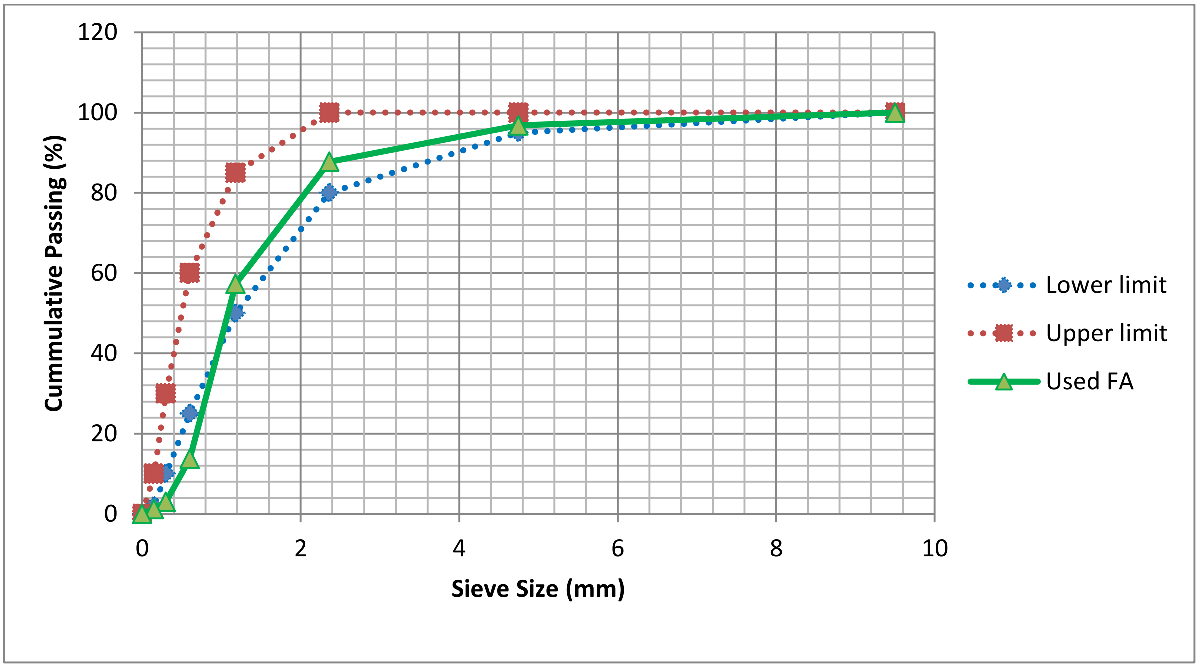

Figure A-1 Gradation curve for Fine Aggregate (FA)

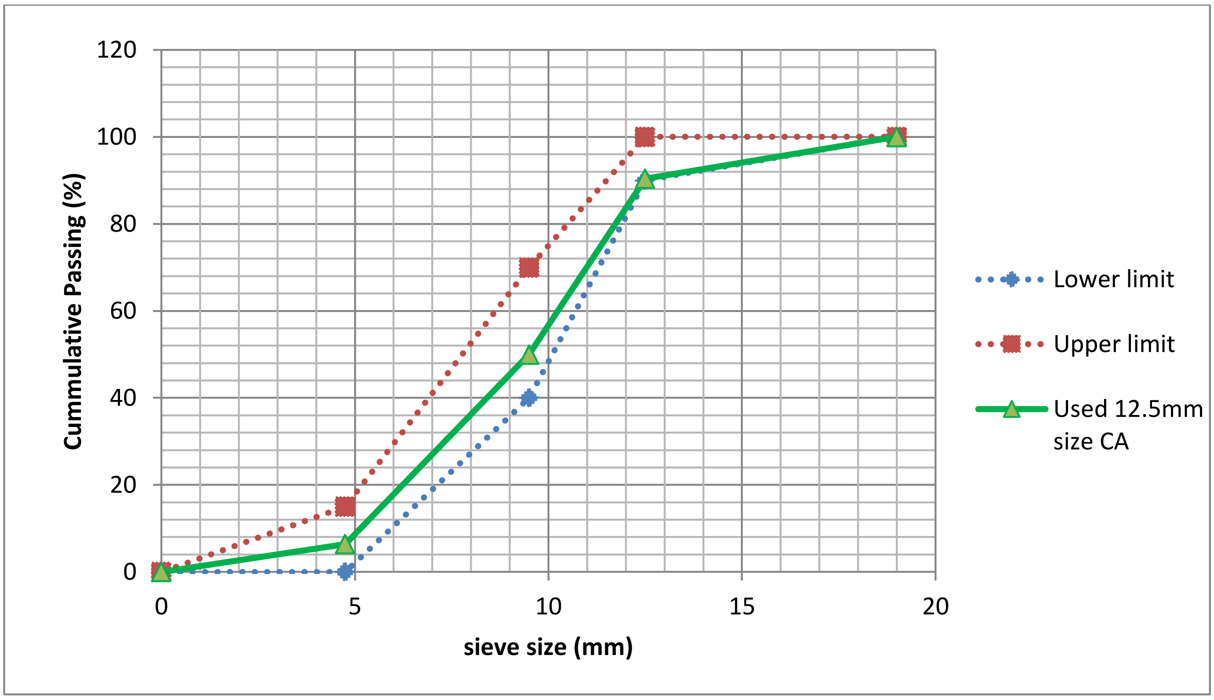

Figure A-2 Gradation curve for Coarse Aggregate (CA)

A-2 **Mechanical properties of used longitudinal and lateral reinforcement bar**

Table A-1Mechanical properties of used longitudinal and lateral reinforcement bar

Sample	DIA		Average Dia(mm)	Area (mm2)	Yield Load (kN)	Failure Load (kN)	Final elongation (cm)	Mass(g)	Length (cm)	Yield Stress (MPa)	Tensile Stress (MPa)	Ultimate Strain (%)	Average Yield Stress (MPa)	Average Tensile Stress (MPa)	Density	Average Density
	D1 (mm)	D2 (mm)														
Φ8,1	7.68	8.54	8.11	51.66	20.6	26.4	2.5	370	100	398.78	511.06	12.50	439.64	550.12	7162.57	7449.49
Φ8,2	7.48	8.7	8.09	51.40	21.4	26.8	1.7	370	100	416.32	521.37	8.50			7198.03	
Φ8,3	7.14	8.24	7.69	46.45	23.4	28.7	1.7	371	100	503.82	617.93	8.50			7987.86	
Φ8',1	7.58	8.53	8.06	50.96	27.2	32.3	1	309	80	533.76	633.84	5.00	524.81	619.33	7579.60	7410.42
Φ8',2	7.66	8.61	8.14	51.98	28.2	32.8	2	306	80	542.55	631.06	10.00			7359.11	
Φ8',3	7.59	8.62	8.11	51.59	25.7	30.6	2.6	301	80	498.12	593.10	13.00			7292.55	
Φ12,1	10.83	11.92	11.38	101.62	34.6	49.8	3.5	752	102	340.47	490.04	17.50	339.97	495.30	7254.78	7493.14
Φ12,2	10.57	11.82	11.20	98.43	34.4	49.8	4.4	761	101	349.48	505.93	22.00			7654.63	
Φ12,3	10.69	11.81	11.25	99.40	32.8	48.7	4.2	760	101	329.97	489.93	21.00			7570.01	
Φ12',1	11.17	12.33	11.75	108.43	62.5	72.8	6.3	696	80	576.39	671.37	31.50	582.59	685.30	8023.29	7754.65
Φ12',2	11.5	12.96	12.23	117.47	66.4	77.5	5.8	687	80	565.23	659.72	29.00			7310.09	
Φ12',3	11.13	12.49	11.81	109.54	66.4	79.4	6	695	80	606.15	724.82	30.00			7930.56	
Φ14,1	13.6	14.65	14.13	156.70	73.6	98	2.3	1167	100	469.69	625.40	11.50	460.32	614.60	7447.37	7477.86
Φ14,2	13.52	14.61	14.07	155.37	70.5	94	2.4	1187	101	453.75	605.00	12.00			7564.13	
Φ14,3	13.56	14.79	14.18	157.81	72.2	96.8	2.8	1183	101	457.51	613.39	14.00			7422.09	

NB: Density and average density has unit (kg/m^3)

A-3 Mix design for SCC and VC concrete

Table A-2Mix design for SCC concrete

Trial one mixing design for SCC, f_{cu} = 45MPa, (based on EPG, EFNARC, JSCE2007 rational mix design method)			
	Specific Gravity (SG) of Coarse Aggregate (CA)=	2.86	
	SG of Fine Aggregate (FA) =	2.23	
	SG of water=	1	
	SG cement=	3.15	
	Density of water=	997.75	Kg/m^3 at room temperature
	Density of concrete=	2400	kg/m^3
	f_{cu} =	45	MPa
Where f_{cu}: Target avg. cubic compressive strength at 28 days			
	Select Total cement content =	**450**	kg/m^3
	Selection of water cement ratio =	0.4	>=0.32 and <=0.4
	water content =	**180**	kg/m^3
Mix calculations			
	Volume of concrete=	1	m^3
	Volume of cement =	0.143	m^3
	Volume of water (VW)=	0.180	m^3
	Mass of admixture =	**6.750**	Kg
	Volume of admixture (VAD) =	0.008	m^3
	Volume of air (VA) =	0.02	m^3
	Total aggregate volume =	0.649	m^3
	Total aggregate mass =	1557.35	
	Initial Mass of Fine aggregate=	778.68	Kg
	Volume of Fine aggregate (VFA)=	0.350	m^3
	Mass of coarse aggregate=	778.68	Kg
	Volume of Coarse aggregate (VCA)=	0.273	m^3
	Vo=VCA+VFA+VA+VAD+VW=	0.974	m^3
	1-Vo=	0.026	m^3
	Add on Coarse A	37.166	Kg
	Mass of coarse aggregate=	**815.84**	Kg
	Volume of Coarse aggregate=	**0.286**	m^3
	Add on Fine Aggregate	28.98	Kg
	Mass of Fine aggregate=	**807.66**	Kg
	Volume of Fine aggregate=	**0.363**	m^3
	CHECK VOL-	**1.000**	m^3
	Total mass=	**2260.25**	kg/m^3
FINAL MIX PROPORTIONS (kg/m3)	Cement=	**450**	kg/m^3
	Corrected CA=	**832**	kg/m^3
	Corrected FA=	**820**	kg/m^3
	Water=	**180**	kg/m^3

Mixing Design for VC, f_{cu} = 45MPa, maximum aggregate 12.5mm size (ACI MIX DESIGN; ABSOLUTE VOLUME METHOD)

Specific Gravity (SG) of Coarse Aggregate (CA)=	2.86	
Specific Gravity (SG) of Fine Aggregate (FA) =	2.23	
SG of water=	1	
SG cement=	**3.15**	
Density of water=	997.75	At room temperature
Bulk Compacted Density of maximum 10mm size CA=	1511	kg/m^3
Bulk Compacted Density of maximum 20mm size CA=	1598	kg/m^3
f_{cu}=	45	N/mm^2
where fcu: Target avg. cubic compressive strength at 28 days		
f_{ck}=	36	N/mm^2
w/c=	0.45	w/c<=0.45
Air content=	0	m^3
water content=	199	kg/m^3
cement content=	442	kg/m^3
CA content=	854.98	kg/m^3
FA content=	801.51	kg/m^3
Corrected CA	860.96	kg/m^3
Corrected FA=	825.55	kg/m^3
Total mass=	*2327.73*	kg/m^3
Surface moisture of FA and CA=	0	
corrected water=	216	kg/m^3
FINAL MIX PROPORTIONS		
Water=	**216**	kg/m^3
Cement=	**442**	kg/m^3
CA=	**860.96**	kg/m^3
FA=	**825.55**	kg/m^3

Table A-3Mix design for VC concrete

A-4 Mix design trials for obtaining fresh properties of SCC concrete

Trials	Cement (kg/m3)	w/c	FA (kg/m3)	CA(kg/m3)				SP(%)	Retardant(%)
				Total	10mm	12.5mm	20mm		
1	450	0.42	812.33	820.57	492.34	0.00	328.23	3	0.00
2	500	0.48	832.78	747.75	747.75	0.00	0.00	2.5	1.00
3	500	0.48	840.30	669.00	669.00	0.00	0.00	2.5	0.50
4	550	0.48	789.80	628.79	628.79	0.00	0.00	2.5	0.75
5	525	0.44	815.05	648.89	648.89	0.00	0.00	2.5	0.00
6	525	0.44	815.05	648.89	648.89	0.00	0.00	2.4	1.00
7	550	0.4	756.28	734.70	734.70	0.00	0.00	3.2	0.00
8	550	0.34	789.80	628.79	628.79	0.00	0.00	2.5	0.00
9	550	0.33	789.80	628.79	628.79	0.00	0.00	2.5	0.00
SCC1	550	0.33	789.80	628.79	628.79	0.00	0.00	2.3	0.00
SCC2	550	0.33	789.80	628.79	628.79	0.00	0.00	2.0	0.00
SCC3	550	0.345	789.80	628.79	314.40	314.40	0.00	2.1	0.00
SCC4	550	0.36	789.80	628.79	314.40	314.40	0.00	2.1	0.00

Table A-4 Mix design trials for SCC concrete

A-5 Fresh properties of investigated SCC trials

Trials	Slump Flow(mm)	Slump T500(sec)	V-Funnel(sec)	V_{T5}min(sec)	L-Box(H_2/H_1)	Remark
1	565	3.5	…	…	Blocked	X
2						X
3	665	1.6	5.3	7	0.7	X
4	735	1.8	…	…	…	X
5	650	2.6	9.5	…	…	X
6	600	3.16	16		0.74	X
7	665	3.75	..	…	…	X
8	682.5	3.63	19		0.89	B
9	665	6.2	32		…	B & V
SCC1	660	3.68	15	25	0.9	V
SCC2			14.64	21.94		V
SCC3	700	3.6	13	18	0.89	NB
SCC4	680	2.64	12	18	0.89	LB

NB: X = Don't satisfy the SCC fresh properties, B = bleeding, LB = little bleeding, NB = No Bleeding, and V = viscous

Table A-5 The observed SCC concrete fresh properties,

A-6 Summary of strength test result for SCC and VC concrete, 7 and 28 days

Trials	No.	Test Age (days)	Dimensions(cm)			Weight(gm)	Volume (cm3)	Failure Load(kN)	Comp-Strength	Unit Weight
			L	W	H					
TR9	1	7	15	15	14.8	7383	3330	629.00	27.95	21.75
	2		15	15	15	7439	3375	615.40	27.35	21.62
	3		15	15	15	7438	3375	630.60	28.02	21.62
							Mean	**625.00**	**27.77**	**21.66**
SCC1	1	9	15	15	15	7499	3375	700.10	31.11	21.80
	2		15	15	15	7312	3375	701.90	31.20	21.25
	3		15	15	15	7276	3375	600.50	26.69	21.15
							Mean	**667.50**	**29.67**	**21.40**
SCC1	1	14	15	15	15	7314	3375	709.30	31.53	21.26
	2		15	15	15	7392	3375	721.80	32.08	21.49
	3		15	15	15	7348	3375	703.90	31.28	21.36
							Mean	**711.67**	**31.63**	**21.37**
SCC2	1	14	15	15	15	7418	3375	878.40	39.04	21.56
	2		15	15	15	7444	3375	855.90	38.04	21.64
	3		15	15	15	7505	3375	866.20	38.50	21.81
							Mean	**866.83**	**38.53**	**21.67**
SCC2	1	28	15	15	15	7566	3375	962.5	42.76	21.99
	2		15	15	15	7567	3375	927.3	41.21	21.99
	3		15	15	15	7539	3375	900.8	40.04	21.91
							Mean	**930.20**	**41.34**	**21.97**
SCC3	1	7	15	15	15	7346	3375	858.70	38.17	21.35
	2		15	15	15	7329	3375	939.80	41.77	21.30
	3		15	15	15	7334	3375	853.90	37.95	21.32
							Mean	**884.13**	**39.30**	**21.32**
SCC3	1	28	15	15	15	7587	3375	1070.1	47.56	22.05
	2		15	15	15	7556	3375	981.2	43.61	21.96
	3		15	15	15	7611	3375	1045.4	46.45	22.12
							Mean	**1032.23**	**45.87**	**22.05**
SCC4	1	7	15	15	15	7414	3375	810.00	36.00	21.55
	2		15	15	15	7358	3375	767.80	34.13	21.39
	3		15	15	15	7378	3375	813.80	36.17	21.45
							Mean	**797.20**	**35.43**	**21.46**
SCC4	1	28	15	15	15	7401	3375	937.5	41.36	21.51
	2		15	15	15	7415	3375	914.5	40.65	21.55
	3		15	15	15	7549	3375	953.7	42.39	21.94
							Mean	**935.23**	**41.47**	**21.67**

NB: Compressive strength is (in MPa), and Unit Weight is (in kN/m^3)

Table A-6Summary of Compressive strength test result for SCC concrete trials, 7 and 28 days control cube compressive strength

Table A-7 Splitting tensile strength test result of 7 and 28 days for SCC

S.No.	Days	Diameter (cm)	Height (cm)	Mass(g)	Volume (cm3)	Failure Load(kN)	Splitting tensile (MPa)	Weight (kN/m^3)
1	7	10	20	3482	1570.8	108.3	3.45	21.75
2		10	20	3484	1570.8	115.2	3.67	21.76
3		10	20	3510	1570.8	88.9	2.83	21.92
					Average=	104.13	**3.31**	21.81
1	28	15	29.5	11895	5213.09	229.4	3.30	22.38
2		15	29.5	11875	5213.09	247.3	3.56	22.35
3		15	29.5	12000	5213.09	246.1	3.54	22.58
					Average=	240.93	**3.47**	22.44

Table A-8 Splitting tensile strength test result of 7 and 28 days for VC

S.No.	Days	Dia(cm)	Height(cm)	Mass(g)	Volumes (cm3)	Failure Load(kN)	Splitting tensile (MPa)	Weight (kN/m^3)
1	7	10	20	3605	1570.8	73.4	2.34	22.51
2		10	20	3685	1570.8	99.8	3.18	23.01
3		10	20	3640	1570.8	91.4	2.91	22.73
					Average=	**88.20**	**2.81**	**22.75**
1	28	10	20	3600	1570.8	120	3.82	22.48
2		10	20	3610	1570.8	99.3	3.16	22.55
3		10	20	3600	1570.8	104.6	3.33	22.48
					Average=	**107.97**	**3.44**	**22.50**

A-7 Experimental Load-deflection response of reinforced SCC concrete beam specimen

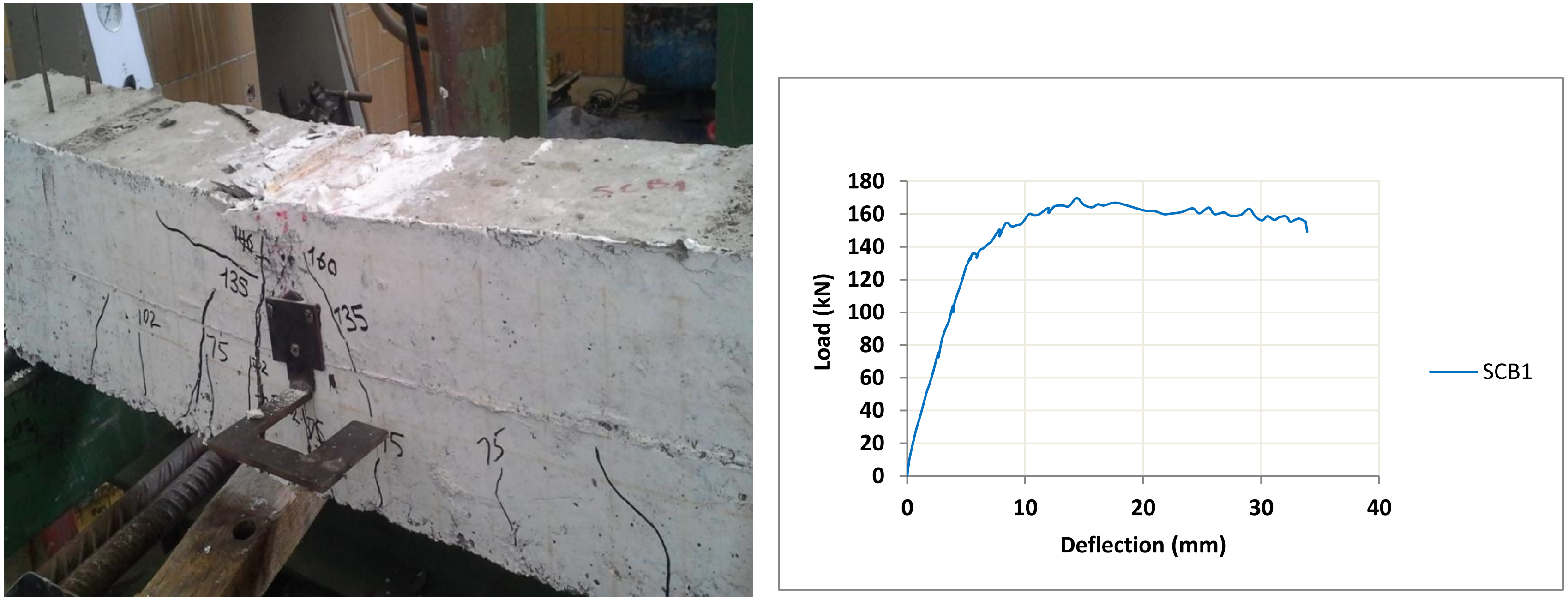

Figure A-3 Crack pattern and Load – deflection response (SCB1)

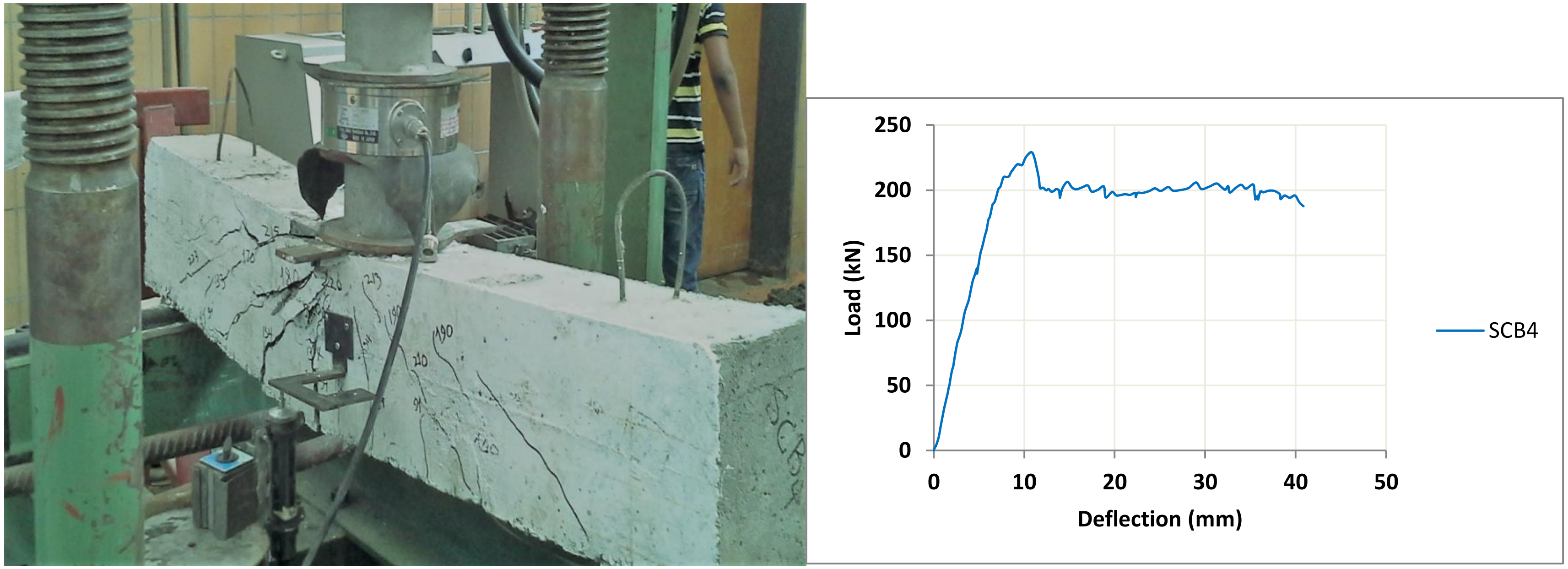

Figure A-4Crack pattern and Load – deflection response (SCB4)