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**EFFECT OF AGGREGATE SIZE ON SHEAR STRENGTH OF
REINFORCED CONCRETE BEAM-COLUMN JOINT**

A Thesis in Structural Engineering

BY MURAD MUSBAH

May 2025

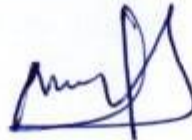
Addis Ababa

A Thesis

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

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UNDERTAKING

I, the undersigned, certify that the research work titled “**Effect of Aggregate Size on Shear Strength of Reinforced Concrete Beam-Column Joint**” is my work. The work has not been presented elsewhere for assessment. Where material used from other sources has been properly referred.

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ABSTRACT

The beam-column connection is an important area within reinforced concrete moment frames. Significant shear is likely to be experienced by this connection during strong ground shaking as the loads are transferred from the beam to the column, and the way in which the connection acts can have a significant influence on how the whole structure is going to perform. Much of the literature simplified the connection as behaving rigid, and did not take into account that we have high shear forces concentrated within the connection. Ultimately, failure in shear is very brittle at the connection and we would not want to see this structurally in a seismic region.

The performance of beam-column joint comes from proper detailing of reinforcement and the strength of concrete. General property of concrete, strength, and durability, comes from its ingredient. Aggregate is an important element in concrete mixing and the resultant compression and tensile strength. Concrete failure properties are significantly affected when the size of aggregate change. This research will focus on the effect of aggregate size and volume on shear strength of reinforced concrete beam column joint.

Generally beam-column joint are areas with relative higher congestion of bars. Hence it will be difficult for concrete to pass. Fine aggregates can reach inside whereas aggregate with larger size difficult to reach inside core concrete. This may cause change in composition inside joint that may cause reduction on shear strength of beam column joint.

This research identify how coarse aggregate size affect shear strength of reinforced concrete beam column joint. Based on experimental result of five RC beam-column specimen with 37.5mm, 25mm, 12.5mm, 4.75mm maximum nominal aggregate size and one additional specimen with 25mm but sieved with 9.5 mm sieve mesh at the joint to represent the effect of bar congestion.

Using aggregate with a larger size, typically provides higher shear capacity for the joint. In addition to shear capacity, aggregate size also affects the joint behavior after the peak strength is reached. Specimens with larger aggregates typically fail in a more ductile way than those with smaller aggregate. In addition, there is also higher initial stiffness for larger aggregate size specimens.

Generally the roll of aggregate size and volume is found to be critical for the seismic performance of beam column joint.

ACKNOWLEDGMENTS

At the bottom of my heart, I first and foremost offer my sincerest gratitude to ALLAH for granting me the courage, strength, and good health to complete this endeavor.

My sincere appreciation and highest respect also to my advisor, Dr. Esayas G/Youhannes, whose wonderful advice, absolute sincerity, and incredibly approachable nature were the driving forces toward the successful completion of this research an experience I will forever cherish.

I would also wish to express sincere thanks to my esteemed colleagues and I also extend my acknowledgment to give immense credit to Sadik Muzeyn. This accomplishment would not have been possible without his imperative help. I would further thank Fikru B. Feysel and Wubet A. from the testing laboratory of building materials for their various forms of support.

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CHAPTER 1 INTRODUCTION

1.1 General Background

In a seismic-resistant structure, a well-designed beam-column joint is a key characteristic. Typically, joints suffer significant damage after large forces from earthquakes. Unsafe design and detailing especially at the joints puts the entire structure and its integrity at risk. Beam-column joints need to be able to resist shear due to the effects of an earthquake, so that the adjacent flexural members can develop their inelastic capacities to dissipate large seismic energy. The seismic design philosophy focuses on ductility of the frame as the primary structural behavior to resist lateral forces. Ductility will be determined by the members, and more specifically, beams and columns. Thus, joints have to be ductile enough to allow the beams and columns to reach their load capacity.

Inelastic deformation of structural members under seismic loads leads to significant, visually apparent damage once the elastic limit is surpassed. This damage is characterized by the formation of plastic hinges. While inelastic rotation is concentrated in specific regions of members, joints lack this isolated capacity. Consequently, when the connected members reach their ultimate ductility, any damage concentrated in the joint poses a severe risk. Seismic design philosophy prioritizes the formation of plastic hinges in beams over columns. During a horizontal earthquake, the moments and shear forces on the beams and columns generate internal vertical and horizontal forces acting on the faces of the joint core. These forces create a resultant force, inducing either diagonal tension or compression within the joint. These internal stresses can lead to cracking and crushing of the core concrete. According to (IS 13920, 2016).

When structural members deform beyond their elastic range due to seismic loads, there is considerable and visible failure, primarily as plastic hinges. Plastic hinges may develop in isolated regions in beams and columns, but beam-column joints may not form plastic hinges in a concentrated manner. In the case of a beam-column joint, any damage to the joint considered at the time that the connected member's exhibit their maximum ductility is of considerable concern for the building structure. The principle of seismic design is that the plastic hinges ideally should only form in beams and not columns. When a horizontal earthquake event takes place, the applied

forces on the building frame generates internal vertical and horizontal forces acting on the faces of the joint core. These separate forces together combine forces to develop a resultant force, which induces internal diagonal tension or compression forces in the joint. Diagonal tension forces and diagonal compression forces can produce significant stresses in the joint which can develop cracking and crushing of the core concrete. Per (IS 13920, 2016), if the joint core has a deficient shear resistance, then failure of the core will lead to failure of the structure.

1.2 Statement of the problem

The presence of congested reinforcement in beam-column joint can affect the composition of core concrete. Aggregate with small diameter can reach whereas aggregate with large diameter difficult to reach inside core concrete. In this research cover the effect of coarse aggregate size on shear strength of reinforced concrete beam- column joint.

1.3 Objective

1.3.1 General objective

The main objective of this research is to identify how coarse aggregate size affect shear strength of reinforced concrete beam column joint under cyclic loading.

1.3.2 Specific objective

Identify the effect of aggregate size on post peak failure behavior in beam-column joints, assess the negative impact of congested reinforcement on beam column joint and analyze the influence of aggregate size on diagonal crack patterns.

1.4 Scope

This research will take the role of coarse aggregate size effect on shear strength of reinforced concrete beam-column joint with congested rebar by considerations about only exterior joint T shape beam column joint. Normal strength concrete (NSC) beams and column which are subjected to shear force which have in addition to longitudinal reinforcement.

1.5 Significance of paper

The significant of this research to support structural engineers in recognizing the significant role of coarse aggregate size on joint shear resistance in reinforced concrete, particularly within congested structural elements. Current design codes often lack consideration for the impact of coarse aggregate size in their shear strength equations. This study seeks to demonstrate the contribution of coarse aggregate size to joint shear resistance and recommends that design codes incorporate this effect to ensure adequate shear strength and prevent failures at beam-column joints.

CHAPTER 2: LITERATURE REVIEW

2.1 Theoretical Background

In the reinforced concrete frames, the beam-column joint is one of the most important areas as it connects all the structural members. These joints are critical for any structure for the reason that they help maintain continuity and also are responsible for carrying the loads which are present at the ends of the members (Sarkar et al, 2007). Beam-column joints are one of the most common locations for failure in reinforced concrete beams that is why it is very important as a structural component (Shamim and Kumar, 1999). The reasoning behind the greater sensitivity of their behavior is the highly complex stress distributions combined with rapid changes in geometry of these joints. For a long time, early design methods involving reinforced concrete joints mainly focused on the needs for anchorage. It later came to light that the behavior of these joints depend on lots of things including their shape, amount and detailing of the reinforcement, strength of concrete, and the pattern of load applied to it. Joint strength Performance as defined by (Park and Paulay, 1975) states that:

- (i) the joint should have adequate strength to resist the maximum expected from the frame structure plastic hinge mechanism so as to avoid the need to repair in a difficult to reach region and at the same time prevent the loss of energy being is dissipated is getting through the joint mechanism which would be dominated by the enormous loss of stiffness and strength with repetitive; inelastic cyclic loading.
- (ii) The joint's integral role as a part of the column is highlighted by the fact that potential strength loss within the joint will not weaken the column's capacity.
- (iii) The expected performance of the joints does not need excessive construction difficulties to be imposed by the reinforcing elements (Kaliluthin et al, 2007).

Beam-column joints are subjected to great stress during seismic activity, requiring high strength and stiffness to counteract the internal forces from members. Joint design lacks detail, as pointed out by (Murthy et al, 2000), may lead to catastrophic structural failure during earthquakes and endanger public safety. Recent earthquakes have shown the vulnerability of these joints, in particular the outer connections which receive significantly higher stress concentrations.

2.2 shear in beam column joint

In beam column joint concrete components fail due to external forces applied to the interfaces of the joints. Shear tensile cracks will occur internally if the external force exceeds the concrete's tensile strength. Under cyclic loading, a complex cracking pattern severely degrades strength and stiffness. This results in enhanced joint rotation, considerable shear deformation, and substantial cyclic relative displacement across the joint surfaces; these shifts enable precise observations using optical tracking technologies. Before estimating the shear behavior, it is necessary to calculate the shear force that the joint must resist. In most cases, design vertical and horizontal shear forces are of great importance; however, with the use of beam hinging devices in compliance with modern code prescriptions, it tends to be reasonable to focus solely on the horizontal shear force demand. (Uma and Prasad, 2015).

The combination of shear and flexural stresses within a joint region is quite intricate. In a joint, as a maximum possible functional limit, strain reversal loading capacity in tension and compression cyclic is a governing factor along with transmitted shear forces through its vertical components (Somerville and Taylor, 1972). The internal moments and shear in the adjoining beams and columns will induce a set of primary horizontal and vertical shear forces to act within the joint core face, resulting in different internal shearing stresses in the core. Hence, the joint core will undergo internal diagonal tensile and compressive stresses as these are the most effective. The resultant shear modulus of these stresses, when extreme, will lead to cracking the concrete in the joint crisscrossing diagonally in tension, or compressing it in a crisscross manner by crushing. The lack of appropriate reinforcement will lead to critical failure mode along the planes joining the opposite corners of the joint core.

In the panel zone, diagonal tension and compression stresses will be induced in addition to the direct compression. When the ultimate capacity of the adjacent members is reached, the diagonal tension could be quite severe, and possibly cause a lot of cracking in the concrete. The severity of the diagonal tension relies mostly on the amount of flexural steel and the vertical axial force on column (Park and Paulay, 1975).

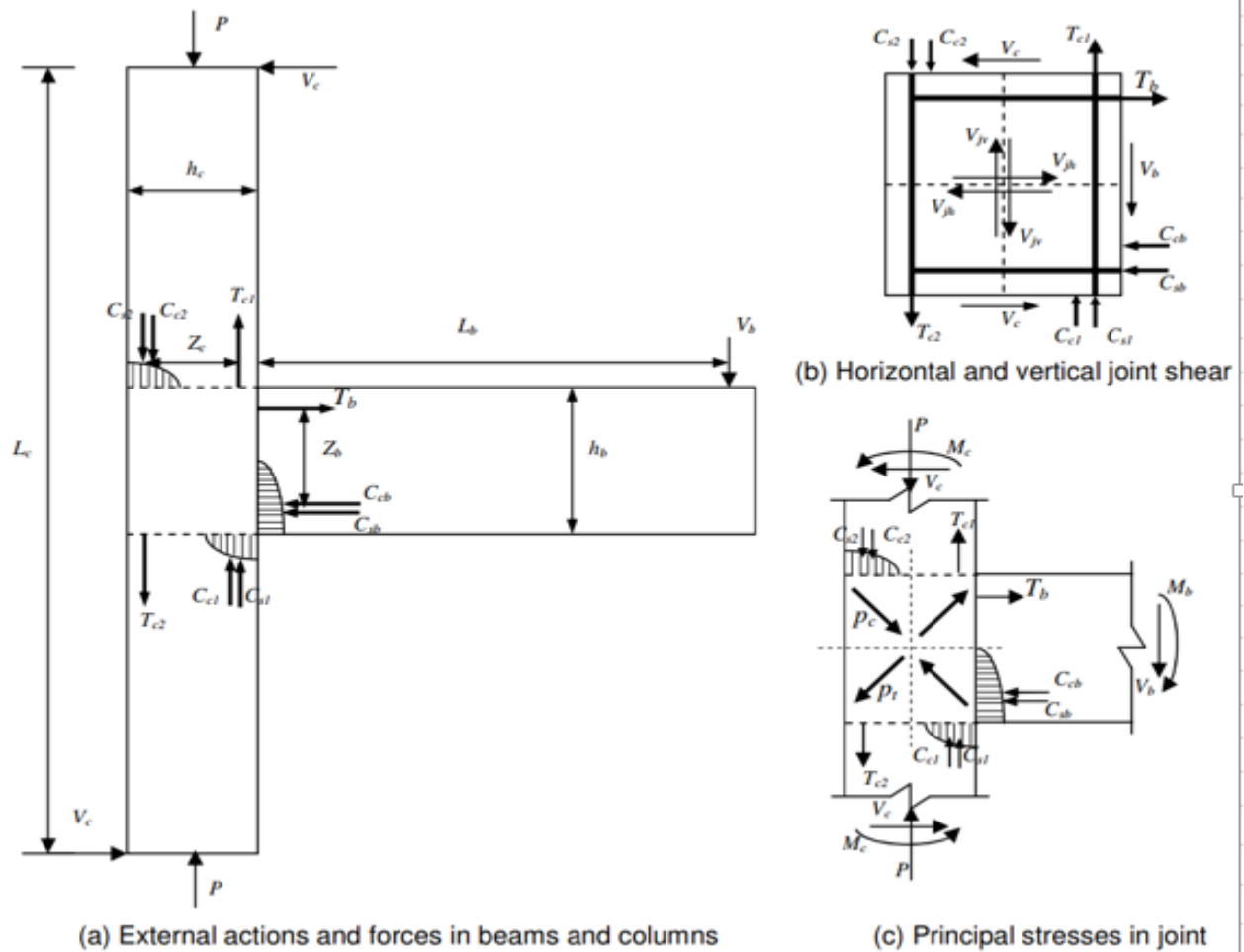


Figure 2.1. Actions at exterior beam-column joint (Siva Chidambaram and Thirugnanam, 2012)

The significant shear forces can be introduced into beam-column joints regardless of whether plastic hinges form at the column faces or at some other location on the beams. Shear forces can cause a failure in the joint core due to shear or bond mechanisms failing, or both (El-Attar et al, 1997). The joint region is subjected to horizontal and vertical shear forces whose magnitude is generally much greater than in the adjacent beams and columns. If these are not designed for, joint shear failure may occur. The reversal of moment across a joint also means that the beam reinforcement must be in tension yield on one side of the joint and compression on the other side of the joint. Large bond stresses to maintain this force gradient across the joint may produce bond failure and corresponding reduction of moment capacity along with unacceptable drift.

2.3 Beam-Column Joint Failure Mechanism

Failure mechanisms clearly is the primary requirement for the designing of joints that are capable of withstanding forces. In seismic areas, RC structures typically follow the strong column-weak beam design philosophy (Somerville and Taylor, 1972). This technique is advantageous because it results in the inelastic deformation of the beam plastic hinges that prevents the formation of the plastic hinges in columns, so, the soft story mechanism, which is dangerous, does not develop. Generally, a beam-column joint can fail because of the following reasons (Kumar and Sharad, 1988): formation of a plastic hinge in the beam near the joint, interface formation of a plastic hinge in the column close to the joint core and development of a diagonal crack within the joint region.

The strength of a beam-column joint depends on several essential issues: the compressive, shear, and bond strength of the concrete are key, and the tensile strength of the reinforcement within the joint. As indicated by (AlZamel and El-Ghazaly, 1991), the major causes of joint failure are grouped into

1. Anchorage failure
2. Yielding of the reinforcement
3. Crushing of the concrete
4. Diagonal tension crack in structural frames,

In conventional structural frames, loads applied to the slabs are passed through the beam-column joint, which acts as a conduit for the transfer of forces between the beams and columns and. The joint transfers the member forces at the interface of the joint and the connected slab-beam, and beam-column-connected members (ACI-ASCE Committee 352-1985). The transfer of load (also called the synergy of strength) occurs through bonding and detailing practices is critical. Lateral forces, especially seismic, tend to generate high horizontal shear in the joint. The shear stress will cause diagonal cracking. If this is repeated then a network of diagonal cracks can form. When the connected slabs and beams achieve their ultimate capacity the diagonal tension in the joint can achieve high values which can contribute to the formation of extensive diagonal cracking. The diagonal cracks will also decrease the anchorage of the beam steel within the joint. In the most extreme events, there may also be some bending cracks present in the connection joint. In a framed

joint designed adopting a strong column-weak beam, the damage will also be localized to the beam near the column face (Raffaella and Wight, 1992). These flexural cracks will typically be at the junction of the beam ends and the column face.

2.3.1 Failure pattern of beam column joint

The initial action of loading causes flexural cracking in the beam, located near the joint. Next, a diagonal crack comes and grows through the connection joint zone. Upon loading further, failure eventually occurs either due to development of plastic hinge of the beam at the column face or more cracking through the connection zone. Which failure mechanism occurs depends on the amount of reinforcement, detailing practice, and the load in the column (Scott, 1996). Therefore, upon analyzing the behavior of an exterior joint leading to a failure, we can use two phases: (a) a phase that consists of the uncracked situation until diagonal cracking in the connection zone occurs, (b) a phase that deals with the development of diagonal cracking until the final failure of the connection. Once diagonal cracking occurs we can still carry additional load, determined by the amount of steel in the beam. With the component uncracked load transfer occurs primarily by the bond developed at the bend of the steel detail, as shown in Figure 2.2 With diagonal cracking the loss of bond at the bend is compensated through increased bond stresses developed along a greater length of the steel, resulting in large load (Somerville and Taylor, 1972).

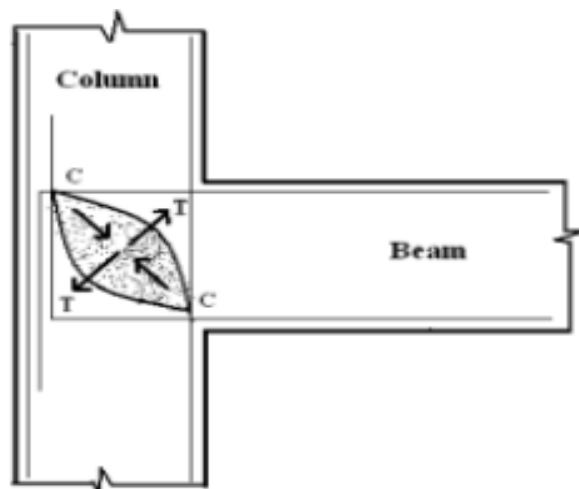


Fig 2.2 Diagonal compression and tension fields in RC exterior beam-column joints (Source: Pradip and Devdas.)

2.4 shear resistance mechanisms in beam column joint

Two principal mechanisms provide shear resistance in a joint: a diagonal concrete strut action and a truss action utilizing the reinforcement. The diagonal strut mechanism comes into play due to the principal diagonal compressive force caused by the combined action of the shear and compression stresses in the critical regions of the beam and the column. The variables that affect the shear strength capacity of the joint will affect the efficiency of each of these shear-resisting mechanisms. Therefore, the total horizontal shear strength that a joint can provide is considered to be an additive effect of the diagonal concrete strut action and that from a truss action.

$$V_{jh} = V_{ch} + V_{sh} \quad (2.1)$$

Where

V_{ch} represents the concrete strut shear strength contribution and

V_{sh} represents the shear strength contribution from the truss mechanism.

A truss mechanism in a joint is reliant on the interaction of bond stresses along the length of the longitudinal reinforcement, the tension strength provided by any lateral reinforcement, and the compressive forces that develop in any diagonal struts formed out of shear cracks in the joint panel. The capacity of the strut will depend on the compressive strength of concrete while the truss capacity will depend on the yield strength of the traversing lateral reinforcement crossing where the likely failure would occur. The diagonal strut can still function in absence of the full transfer of any bond in the joint reinforcement, but the truss action depends on sufficient bond in, and adequate detailing of, the reinforcement. During an earthquake, a considerable bond loss of the beam reinforcement can occur after flexural yielding, if the loading cycles exceed the recommended limit or if unit detailing of reinforcement in the joint is poor. Bond loss decreases the overall effect of the truss mechanism, and leaves the diagonal strut to support most of the joint shear, by taking compression and tension. The transferred tensile force in the beam reinforcement can contribute to increased compressive stress in the strut. The strut will be more vulnerable when subjected to reverse cyclic loading, and adding tensile strain perpendicular to the strut will adversely affect the compressive strength of concrete. The results of the analysis can lead to some shear-compression failure, but the lateral reinforcement will mainly work to confinement.

2.5 Design standard on beam column joint

The United States, Japan, and New Zealand each have different view regarding the shear mechanisms and joint strength which has resulted in no one, single unified method. The Americans recommendations use an empirical method, based on the results of tests, whereby the joint strength is considered to rely primarily on the compressive strength of the concrete, described as a compressive strut in Figure 2.3. The Japanese Guidelines also view the concrete as the primary shear resisting element and amount of reinforcement required based on the shear stress experienced in the joint. The New Zealand code provides a larger scope by including both arch and truss actions in the assessment of joint shear strength that includes steel reinforcement and a concrete strut. The New Zealand code considered yield strength of the plastic hinge of the beam to determine the required reinforcement for the joint and also did not provide a calculation method for joint strength. In the New Zealand methodology:

D_c is the compressive force of the arch mechanism;

D_s is the compressive force of the truss mechanism;

b_a is the width of the strut; and α is the angle of the crack

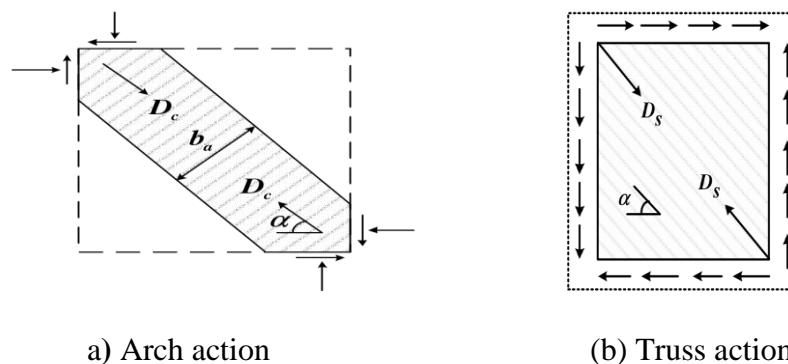


Figure 2.3 arch and truss action

2.5.1 ACI-ASCE Committee 352

ACI-ASCE Committee 352 has two different types of beam-column joints. Type 1 is for members that are expected to not experience any permanent deformation, and Type 2 is for members which were designed to experience large bending and dissipate energy. The committee uses a modified

basic equation (Eqn. 2.2) to produce values for shear strength (V_j) in beam-column joints by essentially considering the concrete compression strength (f_{ck}).

$$V_j = 0.083\gamma \sqrt{f_{ck}} b_j h_c \quad (2.2)$$

$$b_j = \min\left(\frac{b_j + b_c}{2}, b_b + \sum mhc / 2, b_c\right) \quad (2.3)$$

Where,

V_j : Joint shear strength, γ : factor dependent on shape of beam-column joint and seismic zone or non-seismic zone,

f_{ck} : cylindrical concrete compressive strength (MPa),

b_j : effective width of the joint and value satisfying Eqn. 2.2,

h_c : column depth,

b_b : beam width in longitudinal direction,

b_c : joint width, m : 0.3 for the joint that eccentricity between center of beam and column exceeds $b/8$ and 0.5 for other cases.

ACI 318 Chapter 18 outlines seismic provisions with additional requirements for beam-column joint shear strength and reinforcement detailing. It emphasizes "capacity design," meaning joints should be as strong as or stronger than the connected beams and columns, forcing plastic hinge development away from the joint. The code also includes more precise detailing guidelines for both horizontal and vertical shear reinforcement within the joint (American Concrete Institute, 1995).

2.5.2 AIJ 2010

The Architectural Institute of Japan (AIJ) has put forth a nominal joint shear strength equation based on an experimental database of the connections of tested interior and exterior connections between the years of 1986 and 1998. The analysis of the test results considered that shear failure of beam-column joints, concrete compressive strength has a larger effect on the shear strength than

the amount of transverse reinforcement. AIJ's nominal joint shear strength is based on the compressive strut mechanism as the first mode of shear resistance, as illustrated in Equation 2.4

$$V_{ju} = k\Phi F_j b_j h_j \quad (2.4)$$

$$F_j = 0.8 \times f_{ck}^{0.7} \text{ (Nmm}^2\text{)} \quad (2.5)$$

$$b_j = b_b + b_{a1} + b_{a2} \quad (2.6)$$

Where,

k : the factor dependent on the shape of joints (1.0 for + shape, 0.7 for T shape, 0.4 for L shape)

Φ : 1.0 for when transverse beams exist on both sides and 0.85 for the others,

F_j : modified concrete compressive strength expressed as Eqn. 2.4,

b_j : effective width of beam-column joint according to Eqn. 2.5,

h_j : is joint depth ($0.75h_c$ for T and L type and h_c for + and T type),

b_b : beam width,

b_{ai} : the distance between column faces and both beam faces.

2.5.3 Euro code 8 (EN 1998)

The shear capacity is associated with the compressive strength of the concrete and the effects of axial load in the column. Shear Reinforcement: Euro code 8, like ACI, requires shear reinforcement within the joint in the form of hoops or links for resisting shear forces and providing confinement. The shear reinforcement is evaluated based on the design shear force and the effective area for shear.

Shear Resistance of the Joint (Clause 8.4.4, EN 1992-1-1) the design shear force in the joint (V_{jhd}) should satisfy:

$$V_{jhd} \leq V_{jhd \max}$$

Where:

V_{jhd} = shear demand in the joint (determined from frame analysis).

$V_{jhd\ max}$ = maximum shear resistance of the joint.

Shear Resistance of an Interior Joint (No Confinement):

$$V_{jhd\ max} = \eta f_{cd} b_j h_j \quad (2.7)$$

Where:

η = efficiency factor (typically 0.5 for unconfined joints, 0.7 for confined joints).

f_{cd} = design compressive strength of concrete (f_{cd} / γ_c).

b_j = effective joint width (usually taken as the smaller of beam or column width).

h_j = depth of the column in the direction of shear.

Exterior Joints: The resistance is reduced (typically 0.4 f_{cd} for unconfined joints).

$$V_{jhd\ max} = 0.4 f_{cd} b_j h_j \quad (2.8)$$

2.5.4 NZS 3101 (New Zealand Standard for Concrete Structures)

NZS 3101 recognizes two principal mechanisms for beam-column joints to resist shear, a diagonal compression strut carried in the concrete itself, and a truss action utilizing shear reinforcement. The code provides equations that can be used to calculate shear strength from both concrete and shear reinforcement. The total shear strength of the joint is the sum of these two contributions but is limited to a maximum value, based on the compressive strength of the concrete. The New Zealand code is largely based on seismic design and places a strong emphasis on the design of beam-column joints in ductile and limited ductile frames. Further the New Zealand code supports the concept of capacity design for beam-column joints in order to limit the potential for brittle shear failure in these connections.

Strut Contribution (V_{strut})

$$V_{strut} = 0.5\beta f_c' b_j h_j \quad (2.9)$$

Where

β = efficiency factor: 1.0, 0.8, or 0.6 varies based on the joint's location within the structure:

For interior/exterior/corner joints

b_j = effective joint width (usually taken as the smaller of beam or column width).

h_j = depth of the column in the direction of shear.

f_c' = cylindrical compressive strength of concrete

Truss Contribution (V_{truss})

The truss mechanism relies on horizontal hoops and vertical column bars to resist tension.

Horizontal (Shear) Reinforcement Contribution

$$V_{truss,h} = A_{sh} f_{yh} \frac{s}{d} \quad (2.10)$$

A_{sh} = area of horizontal hoops

f_{yh} = yield strength of hoops

d = effective depth of joint

s = spacing of hoops

Vertical Reinforcement Contribution ($V_{truss,v}$)

$$V_{truss,v} = A_{sv} f_{yh} \frac{h_b}{s_v} \quad (2.11)$$

Where:

A_{sv} = area of vertical ties

f_{yh} = yield strength of vertical bars

h_b = beam depth

s_v = spacing of vertical ties

Total Truss Contribution

$$V_{truss,h} + V_{truss,v} \quad (213)$$

Combined Shear Resistance

$$V_n = V_{strut} + V_{truss} \quad (2.14)$$

2.5.5 IS 13920 (Indian Standard for Ductile Detailing of Reinforced Concrete Structures Subjected to Seismic Forces)

IS 13920 defines the nominal shear strength of the joint as a function of the effective area of the joint and the compressive strength of the concrete. Factors are specified to differentiate the levels of confinement provided by beams framing into the joint. Shear reinforcement the code recognizes the requirement for transverse reinforcement (stirrups/hoops) in the joint core area. The amount of transverse reinforcement and spacing are dependent on the shear acting on the joint and size of the connecting members (*IS 13920, 2016*)

2.6 The effect of coarse aggregate size on shear strength

The shear behavior of beams, demonstrated by the experimental program, was shown to be dependent on the type of aggregate present. For instance, beams made from a larger aggregate size exhibited a ductile post-peak failure, compared to brittle behavior for beams with smaller aggregates. Also, beams with larger aggregate sizes had a greater shear capacity (comparatively). The type of aggregate used in this experiment did not have effect on the compressive and tensile strength of the concrete. (Sadik Muzeyn, 2016).

Shear forces are transferred across cracks, often inclined, by aggregate interlock. The interaction between aggregate particles on each side of the crack transfer vertical shear, and provide a substantial portion of the shear capacity of concrete beams, particularly larger aggregates without shear reinforcement. (Walraven, 1981) found that aggregate interlock could transfer a significant amount of shear force. As noted by (Taylor and Brown, 1963), in their test method investigating two modes of shear resistance aggregate interlock or uncracked concrete contributed around 53 - 90 percent of the vertical shear, while dowel action, via longitudinal reinforcement which is not as effective a mechanism contributed about 15 - 25 percent. (Fenwick and Paulay 1968), citing

international evidence, provided a more refined, conventional beam theory breakdown: a 60/20 split between aggregate interlock and dowel action.

The size of aggregate has a major influence on the crack features in RC beams. Larger aggregates create rougher surfaces along cracks resulting in increased frictional resistance known as interlock. While interlock is especially important in the case of beams without shear reinforcement (where concrete is the primary source of shear strength), when compared to units with smaller aggregates, there is evidence available showing that RC beams made with 32 mm aggregates can transfer a greater amount of shear force across critical sections compared to 8 mm. (Somevridge and Taylor, 1972)

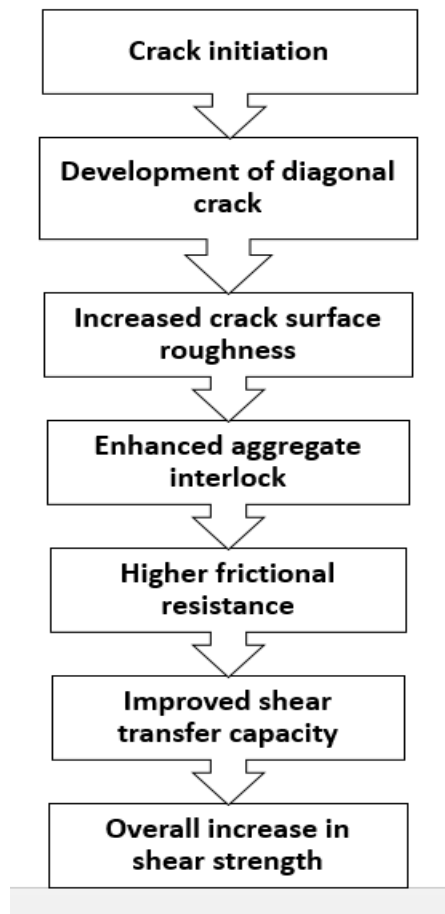


Figure 2.4 flowchart of aggregate interlock mechanism in RC beams (Teshome and Temesgen, 2022)

2.6.1 Influence under static loading

Experimental data strongly supports the idea that aggregate size significantly affects how reinforced concrete (RC) beams behave under shear forces. For example, a study investigating the influence of aggregate size on shear mechanisms under static loading revealed that beams using larger aggregates (32 mm) generally exhibited a greater capacity to resist shear forces at critical points compared to beams with smaller aggregates (8 mm) when subjected to controlled static loads (Teshome and Tmesgen, 2022)

This positive effect can be attributed to the enhanced aggregate interlock achieved with larger aggregates. This improved interlock leads to a better distribution of normal stress across cracks within the beam, ultimately contributing to a more ductile failure mode in situations where shear is the dominant factor in failure.

2.6.2 Influence under impact loading

When external forces are applied to joints, internal shear stresses may become significant, resulting in diagonal tensile stresses. If these stresses exceed the tensile capacity of the concrete, diagonal cracking will occur. With the application of repeated loads, the cracks will propagate within the joint and lessen its strength and stiffness. Thus, joints will bend and experience substantial shear deformation. Before shear behaviors are examined, the shear forces a joint will need to resist must first be assessed. Each design example considered both horizontal and vertical shear force. Newer codes have made substantial advancements in the design of large beams taking advantage of the response of the beam hinged mechanism, thereby allowing designers to consider only the demand of the horizontal shear force at the joint. Based on (Uma and Prasad, 2015).

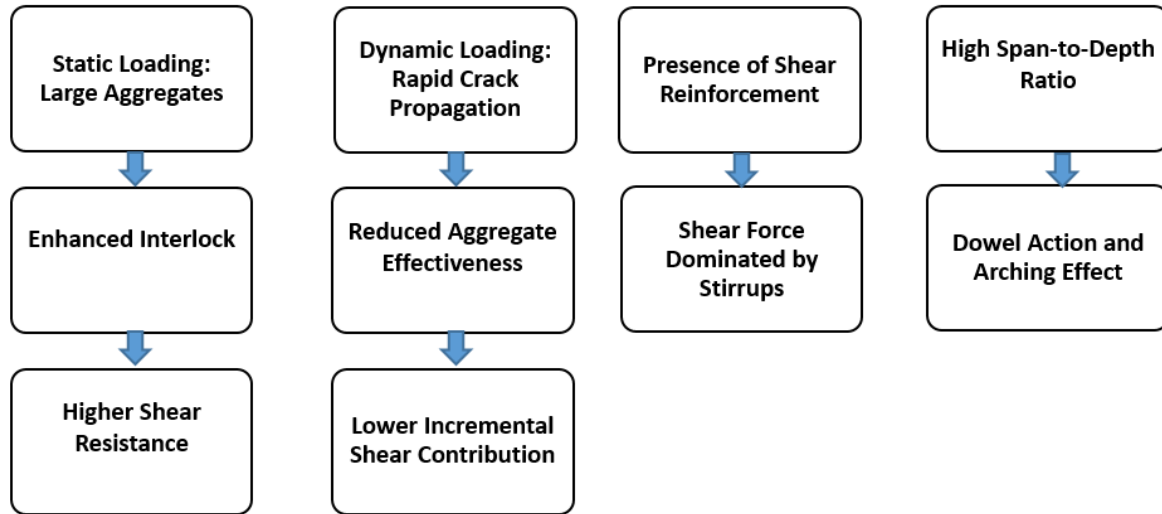


Figure 2.5 Comparative analysis of shear strength contribution (Teshome and Tmesgen, 2022)

CHAPTER 3 EXPERIMENTAL PROGRAM

3.1 Introduction

This chapter describe the type of material, property of material, testing of material, sample preparation, casting of concrete, preparing test setup and conducting test at construction material laboratory at college of technology and built environment.

3.2 Materials

Materials used for this study include coarse aggregate, fine aggregate, cement, water and reinforcement.

3.2.1 Fine aggregate (sand) and coarse aggregate

The experimental program used local available sand and crushed stone coarse aggregate.

3.2.2 Cement

The experimental work utilized commercially available Dangote Portland Pozzolana Cement (PPC) of grade CEM 32.5 R. The physical properties of this cement were described, with a specific gravity of 3.15 g/cm³.

3.2.3 Water

Water is necessary for the chemical reactions between cement and the other component, to allow concrete to set and gain strength, potable water was used for these study in accordance with BS (EN 1008, 2002).

3.3 Experimental program

The research consisted of five beam-column specimens which possessed the same cross-section, reinforcement configuration, concrete mix design, and spacing of the longitudinal reinforcement. This study mainly focused on identifying the effect of aggregate size on shear strength of beam-column joint. All parameter except aggregate size was controlled. T- Type of beam column joint was selected and the cross sectional property of column $L \times h \times w = (2.2 \times 0.3 \times 0.2\text{m})$ and for beam $l \times h \times w = (1.35 \times 0.3 \times 0.2\text{m})$. Four specimens used maximum aggregate sizes of 37.5mm, 25mm, 12.5mm, and 4.75mm. The fifth specimen was created using maximum aggregate size of 25mm concrete that had passed through 9.5mm iron mesh to show the potential congestion at the joint,

and better understand the congestion's impact. Compressive strength and split tensile strength tests were conducted to measure the impact of aggregate size on mechanical properties.

3.3.1 Coarse aggregate

Choosing and preparing coarse aggregate is an important process to identify durable and strong concrete. To meet the ASTM C33 gradation specification for coarse aggregates, the aggregate mixture was first sieved to separate individual sizes starting from 37.5mm to 1.18mm and placed in different plastic bag. After separating coarse aggregate based on sizes, the next steps were combined based on quantity which needed for preparing each individual aggregate size proportions as specified in ASTM C33 gradation. Laboratory testing was conducted to assure the combination of coarse aggregate complied with the specifications to guarantee successful concrete performance.

Table 3.1: Grading requirements for coarse aggregates

Size Number	Nominal Size (Sieves with Square Openings)	Amounts Finer than Each Laboratory Sieve (Square-Openings), Mass Percent													
		100 mm (4 in.)	90 mm (3½ in.)	75 mm (3 in.)	63 mm (2½ in.)	50 mm (2 in.)	37.5 mm (1½ in.)	25.0 mm (1 in.)	19.0 mm (¾ in.)	12.5 mm (½ in.)	9.5 mm (¾ in.)	4.75 mm (No. 4)	2.36 mm (No. 8)	1.18 mm (No. 16)	300 µm (No.50)
1	90 to 37.5 mm (3½ to 1½ in.)	100	90 to 100	...	25 to 60	...	0 to 15	...	0 to 5	...	...	...	...	...	...
2	63 to 37.5 mm (2½ to 1½ in.)	...	...	100	90 to 100	35 to 70	0 to 15	0 to 5	...	...	...	...	...	...	...
3	50 to 25.0 mm (2 to 1 in.)	...	...	...	100	90 to 100	35 to 70	...	0 to 5	...	...	...	...	...	...
357	50 to 4.75 mm (2 in. to No. 4)	...	...	...	100	95 to 100	35 to 70	...	10 to 30	...	0 to 5	...	...	...	...
4	37.5 to 19.0 mm (1½ to ¾ in.)	...	...	...	...	100	90 to 100	20 to 55	0 to 15	...	0 to 5	...	...	...	...
467	37.5 to 4.75 mm (1½ in. to No. 4)	...	...	...	...	100	95 to 100	...	35 to 70	...	10 to 30	0 to 5	...	...	...
5	25.0 to 12.5 mm (1 to ½ in.)	...	...	...	...	...	100	90 to 100	20 to 55	0 to 10	0 to 5	...	...	...	...
56	25.0 to 9.5 mm (1 to ¾ in.)	...	...	...	...	...	100	90 to 100	40 to 85	10 to 40	0 to 15	0 to 5	...	...	...
57	25.0 to 4.75 mm (1 in. to No. 4)	...	...	...	...	...	100	95 to 100	...	25 to 60	0 to 10	0 to 5	0 to 5	...	...
6	19.0 to 9.5 mm (¾ to ¾ in.)	...	...	...	...	...	...	100	90 to 100	20 to 55	0 to 15	0 to 5	...	...	...
67	19.0 to 4.75 mm (¾ in. to No. 4)	...	...	...	...	...	...	100	90 to 100	...	20 to 55	0 to 10	0 to 5	...	...
7	12.5 to 4.75 mm (½ in. to No. 4)	...	...	...	...	...	...	...	100	90 to 100	40 to 70	0 to 15	0 to 5	...	...
8	9.5 to 2.36 mm (¾ in. to No. 8)	...	...	...	...	...	...	...	...	85 to 100	10 to 30	0 to 10	0 to 5	...	...
89	9.5 to 1.18 mm (¾ in. to No. 16)	...	...	...	...	...	...	...	...	100	20 to 55	5 to 30	0 to 10	0 to 5	...
9 ^a	4.75 to 1.18 mm (No. 4 to No. 16)	...	...	...	...	...	...	...	...	100	85 to 100	10 to 40	0 to 10	0 to 5	...

Preparation of coarse aggregate based on ASTM C33 gradation requirement

Table 3.2 aggregate proportion

Nominal Size(mm)	Amounts coarser than each laboratory sieve(square-openings (mm)), Mass percent										
	50	37.5	25	19	12.5	9.5	4.75	2.36	1.18	0.3	pan
37.5 to 19	0	3	77	20							
25 to 12.5	0	0	5	57.5	32.5	5					
12.5 to 4.75	0	0	0	0	5	45	50				
4.75 to 1.18							10	60	30		



Figure 3.1 prepared coarse aggregates

Four different nominal maximum coarse aggregate sizes are chosen for the experiment from ASTM C33 gradation requirement of coarse aggregates and additional one specimen with similar aggregate size with Bcj-25 but method of casting is different. Instead of putting concrete on beam-column joint first put on mesh with spacing of 9.5 mm and then shake on it. The 5th sample is very important to address the actual cases on site (Bcj-9.5-sv). The mesh represent reinforcement congestion on site.

3.3.2 Fine aggregate

Fine aggregate fill the void between coarse aggregate, it pass sieve size 4.75mm and retained on 0.3mm sieve. To get good quality concrete it is important conducting different lab test including silt content specific gravity. Lab test indicate silt content was high, to reduce silt, fine aggregate was washed and covered by plastic bag to control moisture content.

Table 3.3 Summary of material properties

No	Test Description	Cement	Coarse aggregate of each size (mm)				Fine aggregate
			37.5	25	12.5	4.75	
1	Specific Gravity	3.15					
2	Bulk Density		1599	1588	1592	1847	1521
3	Moisture content:		1.11	1.37	1.98	1.56	1.62
4	Water absorption		2.15	2.03	3.14	1.61	4.10
5	Bulk Specific Gravity (SSD basis)		2.53	2.50	2.50	1.58	3.80
6	Silt content						2.00
7	Fineness Modulus						3.26

3.4 Specimen identification

Experimental program consists five reinforced concrete T beam-column section with similar cross section and detailing with varies aggregate size and the last specimen defer from other specimen do to method of concrete application in to beam-column given in figure 3.1. All parameters

- 1) **Bcj-37.5**, No. 4 (37.5 to 9.5 mm)
- 2) **Bcj-25**, No. 5 (25 to 9.5 mm)
- 3) **Bcj-12.5**, No. 7 (12.5 to 2.36 mm)
- 4) **Bcj-4.75**, No. 9(4.75 to 0.30mm)
- 5) **Bcj-9.5-sv**, similar aggregate size with Bcj-25 but sieved on 9.5mm iron mesh.

Table 3.4 Details of investigated specimens

	Height(H)mm	Width(b)mm	Cover(mm)	Maximum aggregate size(mm)
BCJ.37.5	300	200	25	37.5
BCJ.25	300	200	25	25
BCJ.12.5	300	200	25	12.5
BCJ.4.75	300	200	25	4.75
BCJ-9.5-SV	300	200	25	9.5

3.4.1 Design and detailing of beam specimen

Beam and column designed to resist load acting on it. Beam should resist the cantilever action in addition to concentrated load applied. Similarly 165kN axial load applied to the column edge. The reinforcement detailing shown on figure 3.2

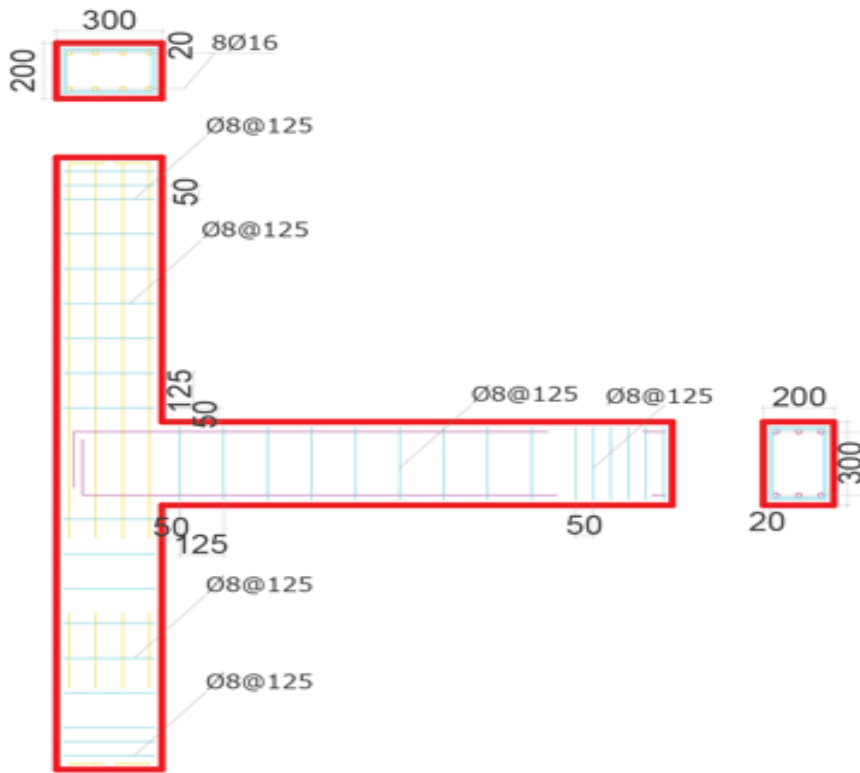


Figure 3.2 beam column section and detail

3.5 Materials

3.5.1 Concrete

The specimens were cast in wooden molds using cast in situ concrete. During the casting process of concrete, samples of 30 cubes concrete 150mmx150mm were prepared for compressive strength and 24 cylinder of diameter 100mmx200mm and 2cylinder of diameter of 150mmx300mm for tensile strength test .12 sample taken from each specimen 6 for tensile and 6 for compressive strength. From each beam specimen and 2 of them were tested 28 days after the casting day and the rest 2 samples were tested the day of testing (See Table 3.6 and Table 3.7). In the mix proportions of concrete (detailed mixed design is attached in the annex part), the target strength was C-25, ordinary Portland cement was used and water-cement ratio was kept at 0.57 (See Table 3.5)

Table 3-5 Mix proportions of concrete

Material	Bcj-37.5	Bcj-25 and Bcj-9.5-sv	Bcj-12.5	Bcj-4.75
Max. aggregate size (mm)	37.5	25.00	12.50	4.75
Free-water (kg/m ³)	17.60	284.40	14.55	15.68
Cement content (kg/m ³)	28.00	405.30	23.55	25.86
Coarse aggregate (kg/m ³)	97.30	1236.04	52.46	26.86
Fine aggregate (kg/m ³)	71.20	976.48	54.16	71.38
Water-cement ratio	0.57	0.57	0.57	0.57

Cube were tested using a compression testing machine (shown in Figure 3.3).



Figure 3.3 Compressive strength testing machine

Table 3.6: Strength at 28th day after casting

Specimen	Compressive strength			Tensile strength		
	(MPa)			(MPa)		
	Cube 1	Cube 2	Average	Cylinder 1	Cylinder 2	Average
BCJ-9.5-SV	24.50	23.80	24.15	1.76	1.94	1.85
BCJ-4.75	24.50	24.70	24.60	1.98	2.34	2.16
BCJ-12.5	25.40	24.90	25.15	2.40	2.50	2.45
BCJ-25	25.70	25.00	25.35	2.20	2.30	2.25
BCJ-37.5	25.42	25.12	25.27	1.95	1.90	1.93

Table 3.7: Strength at testing day

Specimen	Compressive strength			Tensile strength		
	(MPa)			(MPa)		
	Cube 1	Cube 2	Average	Cylinder 1	Cylinder 2	Average
BCJ-9.5-SV	24.80	23.20	24.00	1.86	2.10	1.98
BCJ-4.75	24.80	24.20	24.50	2.10	2.20	2.15
BCJ-12.5	25.55	26.45	26.00	2.30	2.24	2.27
BCJ-25	26.15	25.80	25.80	2.10	2.30	2.20
BCJ-37.5	25.30	25.70	25.50	1.90	2.10	2.00

Note: Factors like variations in the proportioning of materials, inconsistencies in mixing and compaction, and differences in curing conditions can lead to different compressive strength test results for similar mix designs. Subtle variations in the properties of the constituent materials themselves can also play a role. The variability in tensile strength for specimens Bcj-9.5-sv and Bcj-37.5 is relatively on the higher end, between 11-18%. Thus caution shall be taken when using this results for simulation.

3.5.2 Steel

All test specimens utilized 8 mm diameter deformed bars as tie reinforcement, and 16 mm diameter bars as the main reinforcement. Tensile tests were conducted on the longitudinal reinforcement steel as a means of determining the mechanical properties of the steel. The mechanical properties of the reinforcement materials are presented in Table 3.8



Figure 3.4 Tensile Strength testing machine

Table 3.8 Mechanical properties of reinforcement

Specimen No	Diameter(mm)		Yield Stress (MPa)	Failure Stress (MPa)	Elongation (%)	Length (mm)
	D1	D2				
1	7.55	8.75	449.87	546.6	5.2	800
2	7.59	8.77	430.16	526.48	5.3	800
3	7.56	8.79	439.4	544.86	5.1	800
4	15.49	16.85	503.09	699.14	10.1	800

3.5.3 Specimen Fabrication

This section briefly outlines the construction of the test specimens. These specimens were built in the Construction Materials Laboratory. Initially, reinforcement cages were assembled offsite and then placed into the forms, ensuring accurate horizontal and vertical alignment, including leveling. Figure 3.5 shows the completed steel cage.



Figure 3.5: Reinforcement cage and formwork of the specimens

The formwork was constructed using plywood, with mid-span and perimeter stiffeners added to prevent concrete bulging during casting. After the formwork was erected and checked for readiness, the steel cages were placed inside. A 25 mm clear concrete cover was maintained on all sides, as shown in Figure 3.6.



Figure 3.6: Reinforcement cage of specimens inside the formwork

Based on mix design all ingredient mix together by using mixer machine and then concrete was casted in and vibrator was used to consolidate the concrete. The concrete surface exposed to air was moist cured by covering the beams-column with by Casing it with a plastic sheet to avoid evaporation. In curing process both beam – column specimen and sample which taken should kept similar Curing Process to prevent variation on strength.

3.6 Test Setup

The beam-column was setup on steel plates with a roller in between the plates. The steel roller supports were installed on concrete members anchored to the strong floor. A concentrated load was applied using a hydraulic jack (shown in Figure 4-7.a) of maximum capacity 300 kN.



(a) Hydraulic jack

(b) load cell

(c) data logger

Figure 3.7: instrument used when conducting test

3.6.1 Instrumentation

All frame were fully instrumented to measure the applied loads and displacement on the beam and column. In brief, the instrumentation consisted of a load cell which measures the applied load (shown in Figure 3.8), deflection measurement tool also attached (shown in Figure 3.8) for end beam deformation measurement in both up and down direction. All of the instrumentations were connected to a data logger and the experimental data was directly obtained in a USB (shown in Figure 3.8).



(a) Beam column to be tested



(b) reaction on column



(c) Full prepared beam column joint for test

Figure 3.8: test setup

3.6.2 Loading protocol

Loading protocols process were displacement control and 5mm incremental each in every cycle and corresponding loads were registered in both up and down ward direction. This process repeated until 50mm (10th) cycle.

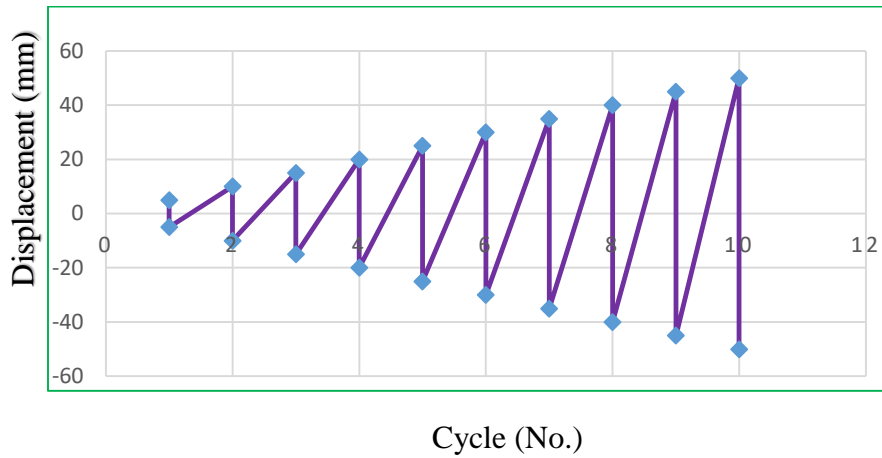


Figure 3.9 Load protocol

CHAPTER 4 EXPERIMENTAL RESULT AND DISCUSSION

4.1 Result

In each of five tested specimens, a typical shear failure occurred, specifically a at beam column joint

Figures 4.1 to 4.5 provide visual documentation of this failure in each beam.



Figure 4:1: joint shear failure in Specimen Bcj-9.5-sv



Figure 4.2 joint shear failure in Specimen Bcj-4.7



Figure 4.3 joint shear failure in Specimen Bcj-12.5

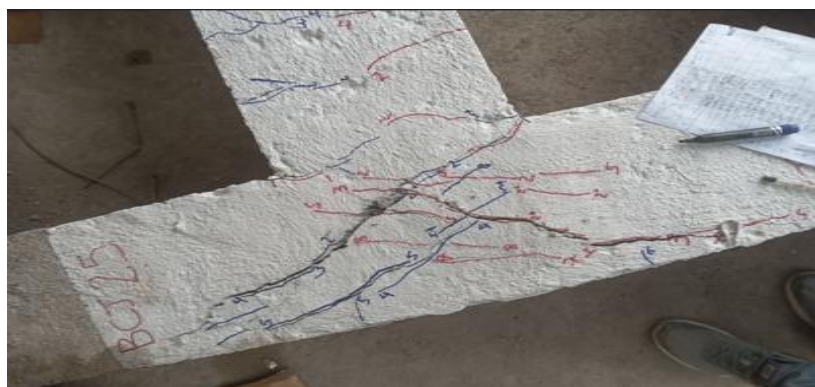


Figure 4.4 joint shear failure in Specimen Bcj-25



Figure 4.5 joint shear failure in Specimen Bcj-37.5

The load deflection diagram for the specimens is shown in the following figures. A medium-sized hydraulic jack was used to apply the load. The jack was situated at top of a load cell and reacted against an overhead rigid steel frame. End Deflection at the beams was measured with displacement measuring transducer. A data logger recorded the load and deflection data in every two second.

4.1.1 Load – Deflection diagram for specimen Bcj-9.5-sv

The peak shear resistance observed in the load deflection curve for specimen Bcj-9.S-sv was 31.12 kN toward left direction at a displacement of 24.73 mm, and 31.5 kN toward right direction at a displacement of 25.2 mm.

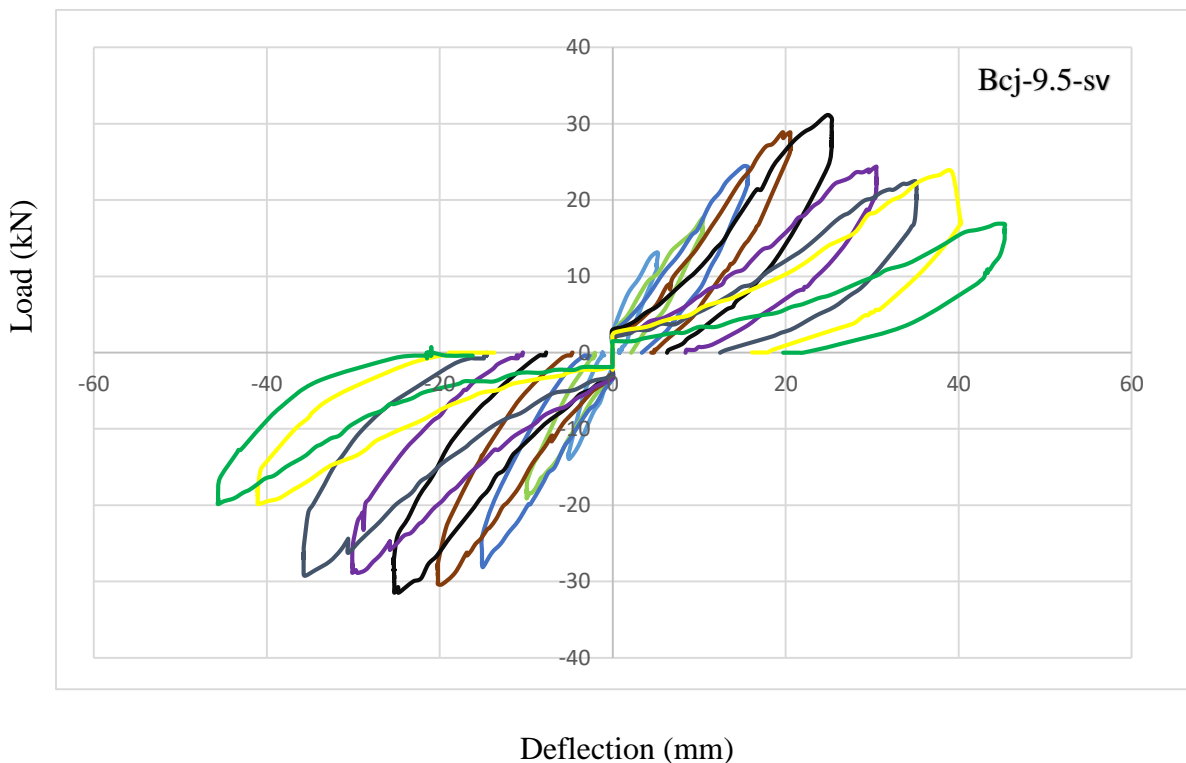


Figure 4.6 Load – Deflection diagram for specimen Bcj-9.5-sv

4.1.2 Load – Deflection diagram for specimen Bcj-4.75

The peak shear resistance observed in the load deflection curve for specimen Bcj-4.75 was 36 kN toward left direction at a displacement of 29.6 mm, and 37.88kN toward right direction at a displacement of 30.07mm.

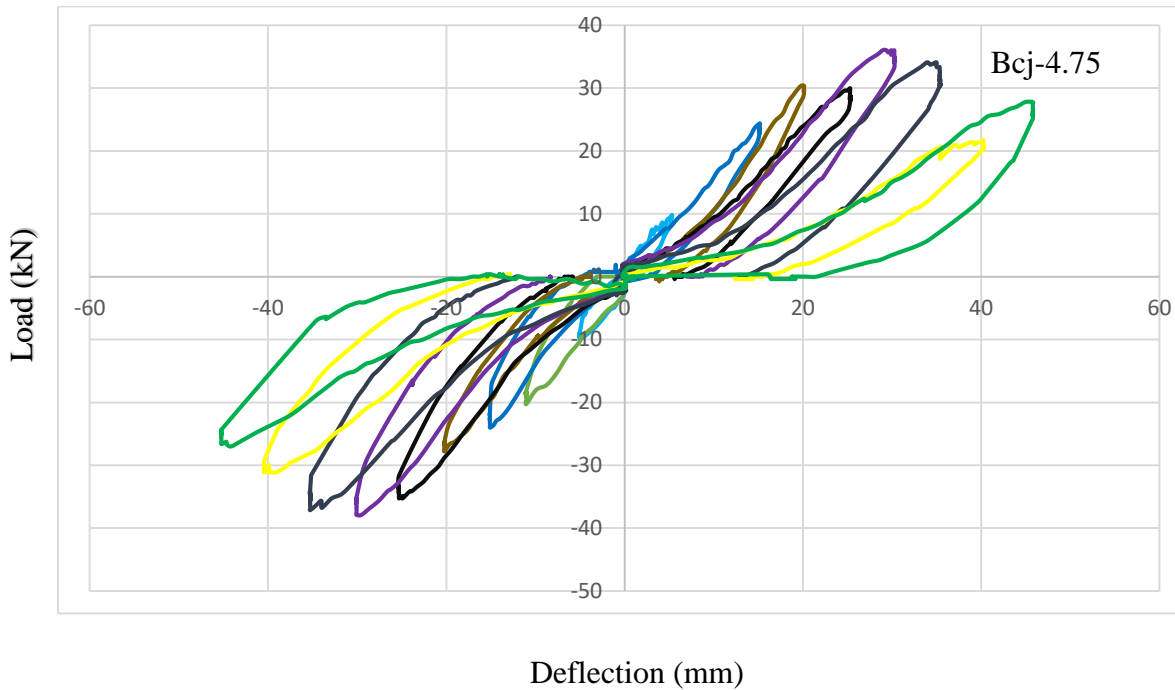


Figure 4.7 Load – Deflection diagram for specimen Bcj-4.75

4.1.3 Load – Deflection diagram for specimen Bcj-12.5

The peak shear resistance observed in the load deflection curve for specimen Bcj-12 was 33 kN toward left direction at a displacement of 30.06 mm, and 42kN toward right direction at a displacement of 24.87mm.

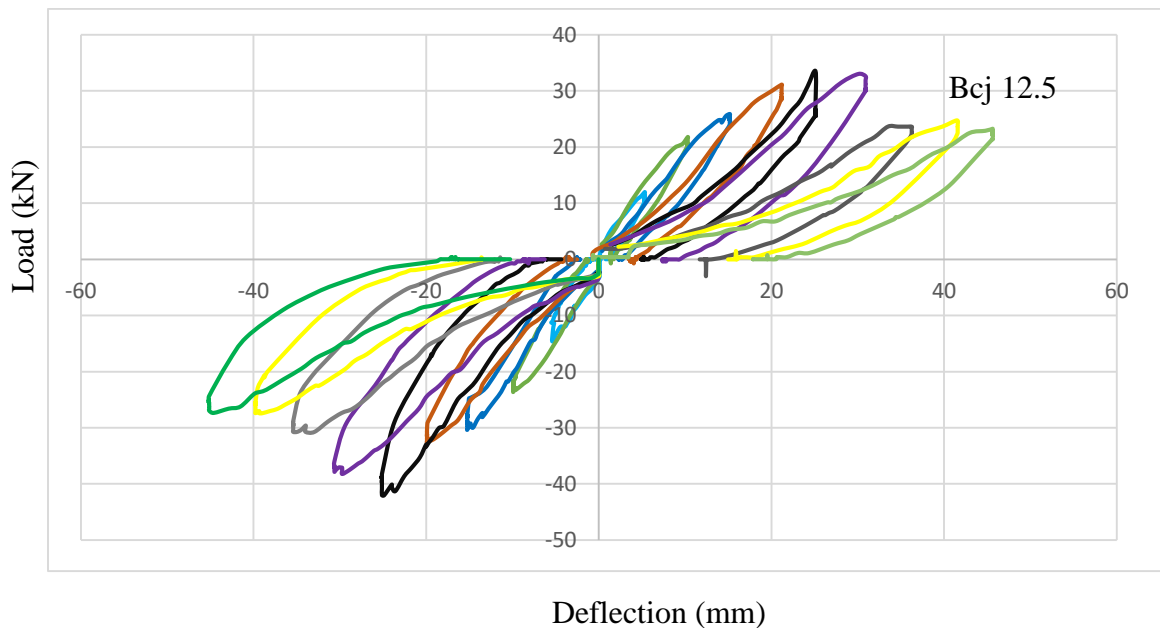


Figure 4.8 Load – Deflection diagram for specimen Bcj-12.5

4.1.4 Load – Deflection diagram for specimen Bcj-25

The peak shear resistance observed in the load deflection curve for specimen Bcj-25 was 42.25kN toward left direction at a displacement of 25.7 mm, and 36.38kN toward right direction at a displacement of 24.75mm.

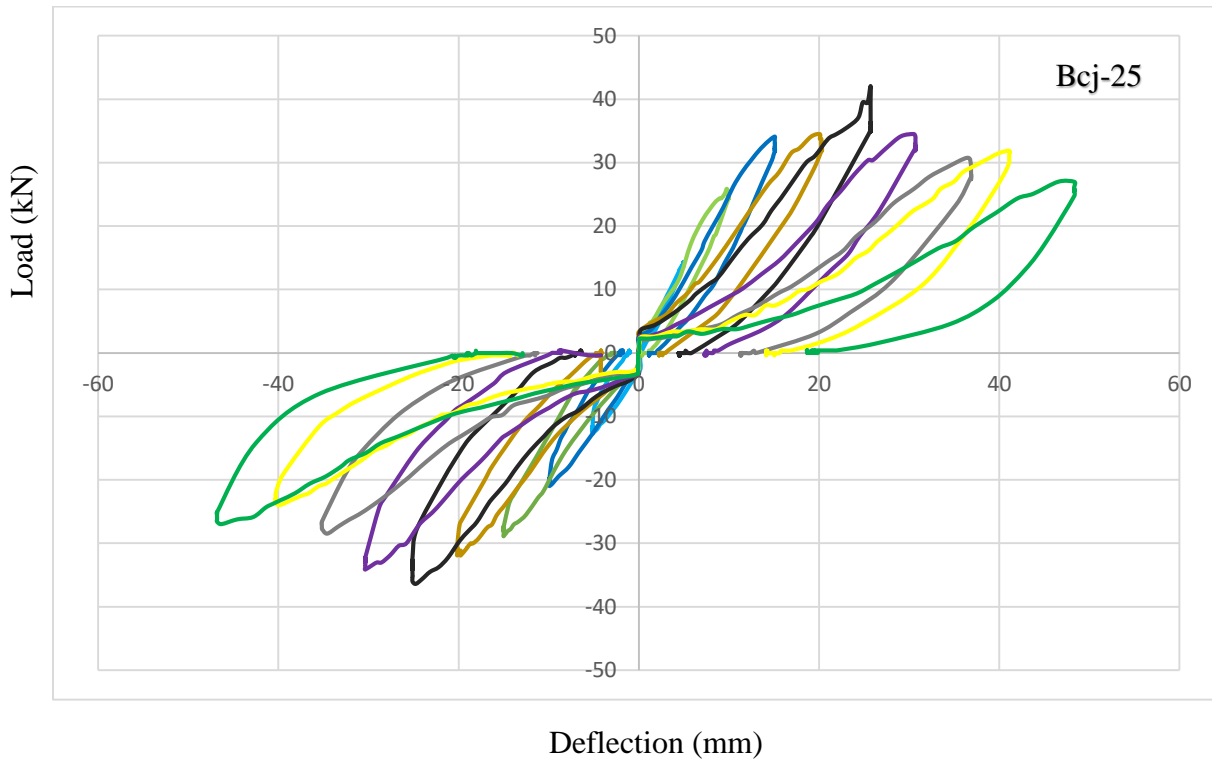


Figure 4.9: Load – Deflection diagram for specimen Bcj-25

4.1.5 Load – Deflection diagram for specimen Bcj-37.5

The peak shear resistance observed in the load deflection curve for specimen Bcj-37.5 was 39kN toward left direction at a displacement of 28.64 mm, and 43.88kN toward right direction at a displacement of 32.9mm.

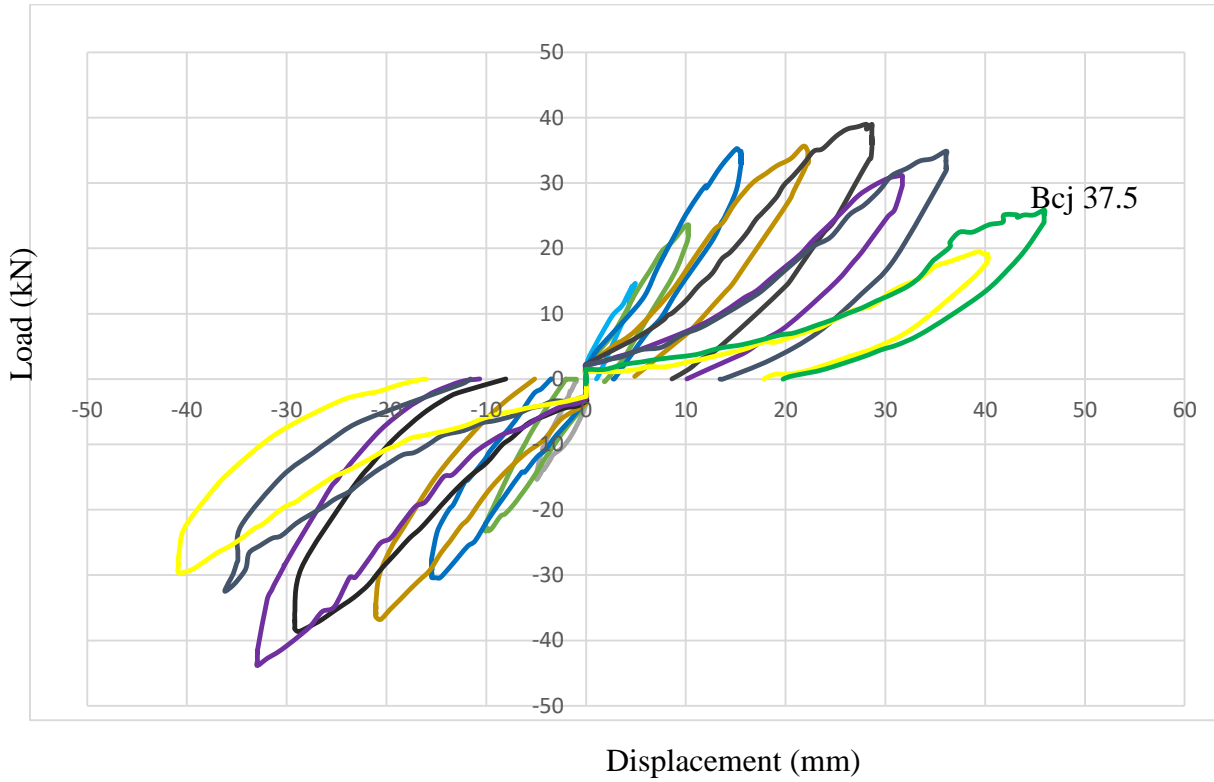


Figure 4.10: Load – Deflection diagram for specimen Bcj-37.5

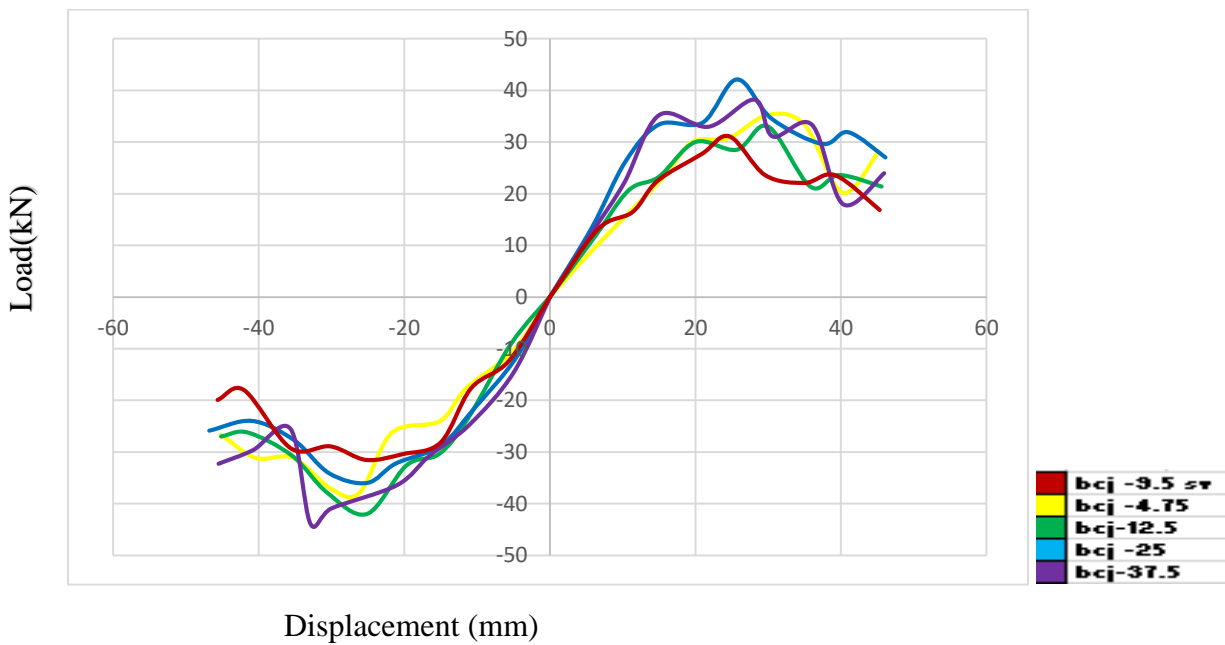


Figure 4.11 Comparison between Loads – Deflection diagrams of all specimens toward left and right direction

4.2 Effect of Aggregate Size

Compressive strength (f_{ck}) is an important factor on beam column joint shear strength. The experimental program yielded specimens of different compressive strengths (see Table 3.7). Because the aim of this research is, to address the influence of aggregate size on shear strength beam-column joint, we should keep compressive strength as control parameter. Based on above reason, the strength of concrete was normalized by $\sqrt{f_{ck}}$. Because different codes and empirical equations account the contribution of compressive strength in the form of $\sqrt{f_{ck}}$

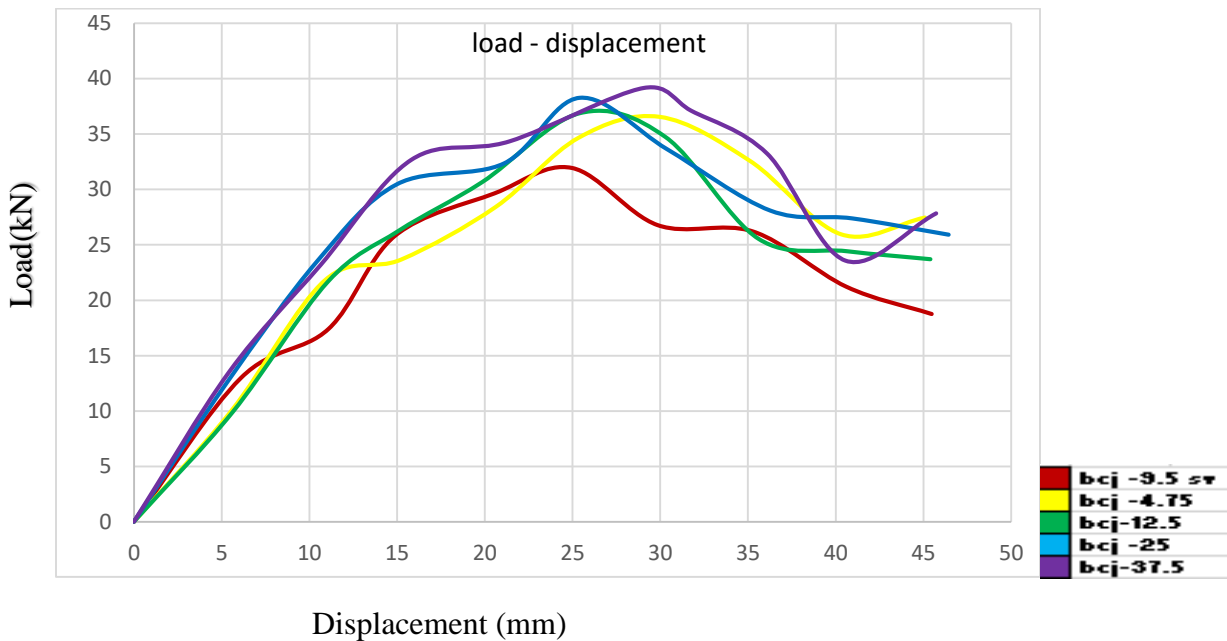


Figure 4.12 Average Load-Deflection diagram for different aggregate sizes with the similar concrete compressive strength

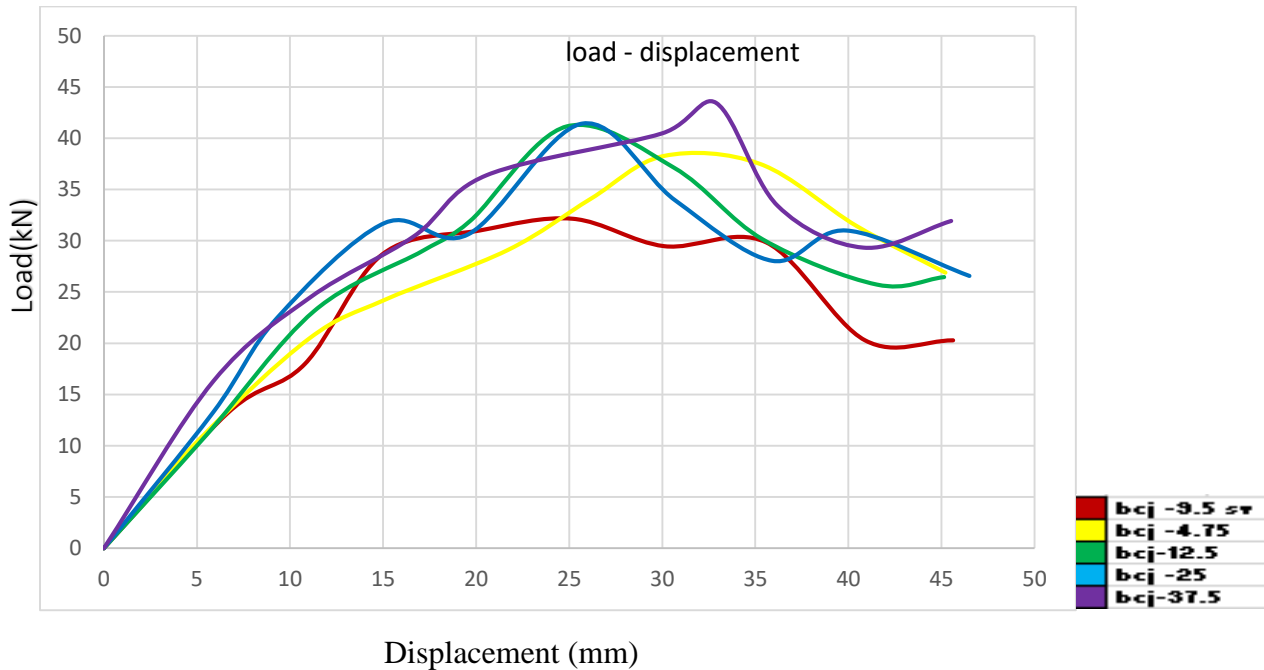


Figure 4.13 envelope Load-Deflection diagram for different aggregate sizes with the similar concrete compressive strength

Figure 4.15 shows, the shear capacity of specimens with large aggregate size are greater than the shear capacity of specimens with small aggregate size. The extreme cases, Bcj-37.5 (with $a_{gmax} = 37.5$ mm) with a peak load is about 43.43 kN and Bcj-9.5-sv (which concrete sieved on 9.5 mm mesh and only mortar can pass) with a peak load 32.14 kN. which indicate 26% joint shear strength reduction similarly Bcj-4.75 ($a_{gmax} = 4.75$ mm) with a peak load is about 38.25 kN which indicate 12.08% joint shear capacity reduction and there is a clear effect of aggregate size on shear capacity of normal strength concrete beam column joint. Not only is the shear capacity, the post peak behavior of the failure is influenced by aggregate size. It can be seen from Figure 6-13, failure of specimens with larger aggregate size are more ductile than specimens with smaller aggregate size. Stiffness is another indication of effect of aggregate size Bcj-37.5 and Bcj-25 had higher initial average stiffness (2.2 kN/mm), whereas Bcj-9.5-sv and Bcj-4.75 low stiffness (1.94 kN/mm).

Heavily congested reinforcement in beam-column joints can hinder proper concrete placement, leading to the formation of voids and honeycombing. These imperfections reduce the effective shear area and disrupt the uniform transfer of shear stresses, potentially causing stress concentrations and increasing the likelihood of cracking and failure. Consequently, the shear capacity of the joint may be lower than the limit specified by Bcj-9.5-sv (Kipcak et al, 2023).

Beyond the reduction in effective area and stress disruption, poor compaction also weakens the bond between the concrete and the shear reinforcement, such as stirrups. This compromised bond reduces the effectiveness of the reinforcement in resisting shear stresses, and it also impairs the contribution of dowel action to the overall shear resistance. Additionally, the voids created by inadequate compaction can act as initiation points for cracks, which can then propagate more easily under shear loading, further decreasing the ultimate shear strength. Ultimately, poor compaction leads to a lower density and often a lower compressive strength of the concrete. Since shear strength is inherently linked to compressive strength, this reduction further exacerbates the vulnerability of the structural element to shear forces

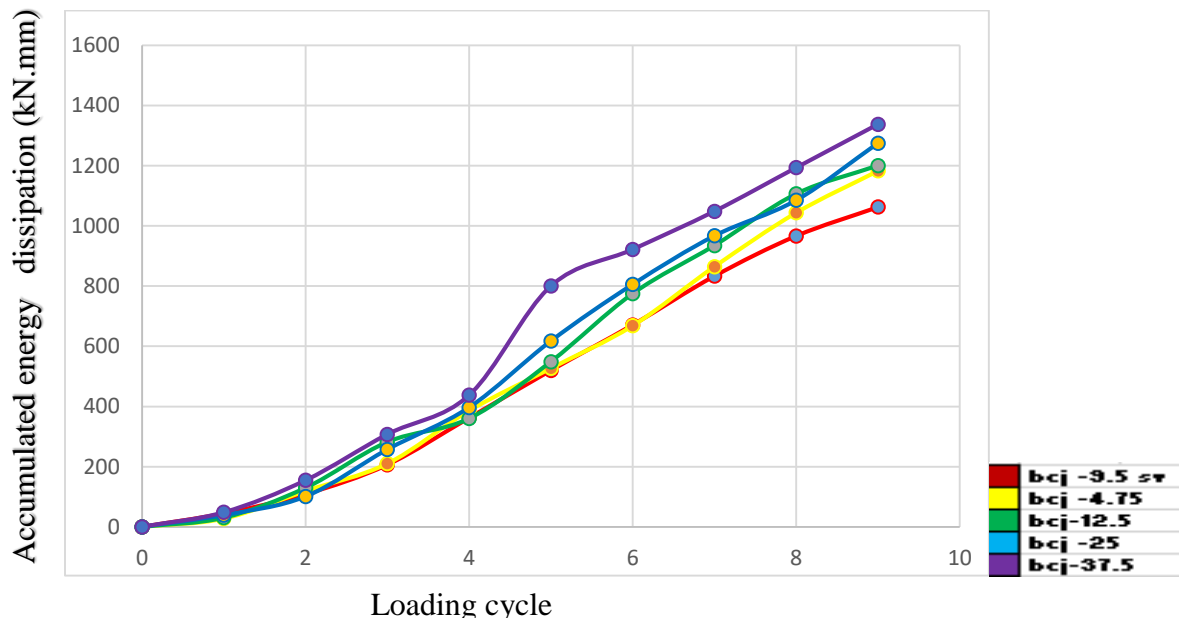
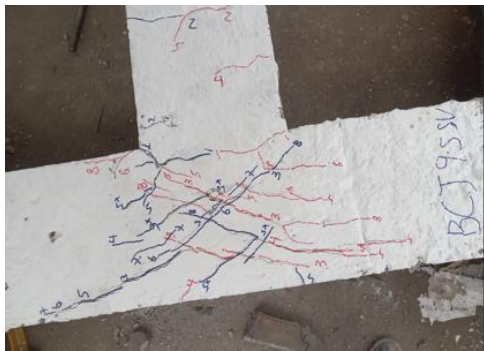


Figure 4.14 Accumulated energy dissipation at each loading cycle

Larger aggregate sizes generally lead to higher energy dissipation in concrete, primarily due to increased fracturing of the aggregates under load. This fracture process, particularly with larger aggregates, contributes to a greater ability for the concrete to absorb and dissipate energy. Energy Dissipation Hysteresis Loop the area under the load-displacement curve represents the energy absorbed by the specimen as it deforms under load, The energy dissipation capacity for beam-column joints Bcj-25 and Bcj-37.5 (1275.1 kNmm and 1337.8 kNmm, respectively) was notably higher than that of Bcj-9.5 (1062.5 kNmm) and Bcj-4.75 (1182.7 kNmm). This represents a significant decrease of 21% in energy dissipation from Bcj-37.5 to Bcj-9.5, and 11.60% reduction

between Bcj-37.5 and Bcj-4.75. Higher aggregates in concrete are more likely to fracture under stress, a reality that directly impacts higher energy absorption under structural deformation. This fracturing of the larger course aggregate also results in more tortuous and complicated crack paths in the concrete matrix. Consequently, such complicated cracking propagation also raises the material's ability to absorb energy. Last but not least, the fracture properties of coarse-aggregates with bigger sizes contribute significantly to improving the overall energy absorbing capacity of the concrete.

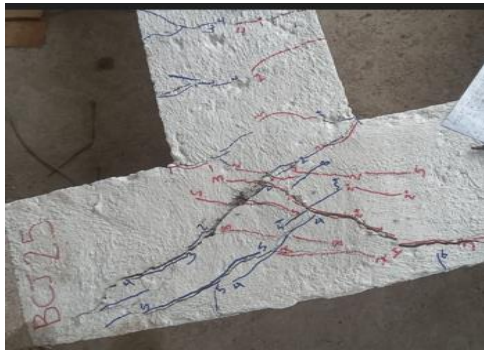
Crack width serves as an indicator aggregate size on shear capacity of beams. In reinforced concrete members, slip typically happens in shear cracks, which allows shear transfer through the mechanism of aggregate interlock. Specimens containing larger aggregates will have greater shear cracks compared to specimens containing smaller aggregates. The larger the coarse aggregate size, the higher the roughness of the crack surfaces and thus the shear stresses that are transferred through the cracks. However, in high-strength and some lightweight concretes, cracks may penetrate through the aggregates instead of around them, forming smoother crack surfaces. Smoothness reduces the efficiency of shear transfer by aggregate interlock, thus lowering the shear capacity of the beam column joint. Bcj-9.5-sv and Bcj-4.75 had small opening compare to Bcj-25 and Bcj-37.5.



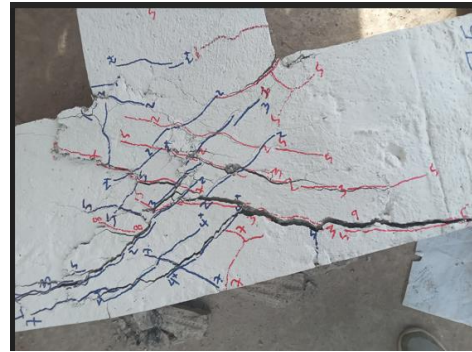
Bcj-9.5-sv



Bcj-12.5



Bcj-25



Bcj-37.5

Figure 4.15: comparison of eight cycle crack width

4.3 Comparison of Code equations with experimental results

Formulas adopted in different Codes of practice used for estimating the beam column joint shear capacity were described in chapter 2. There was no consideration taken to account aggregate size when formulating those equations discussed in chapter 3 is

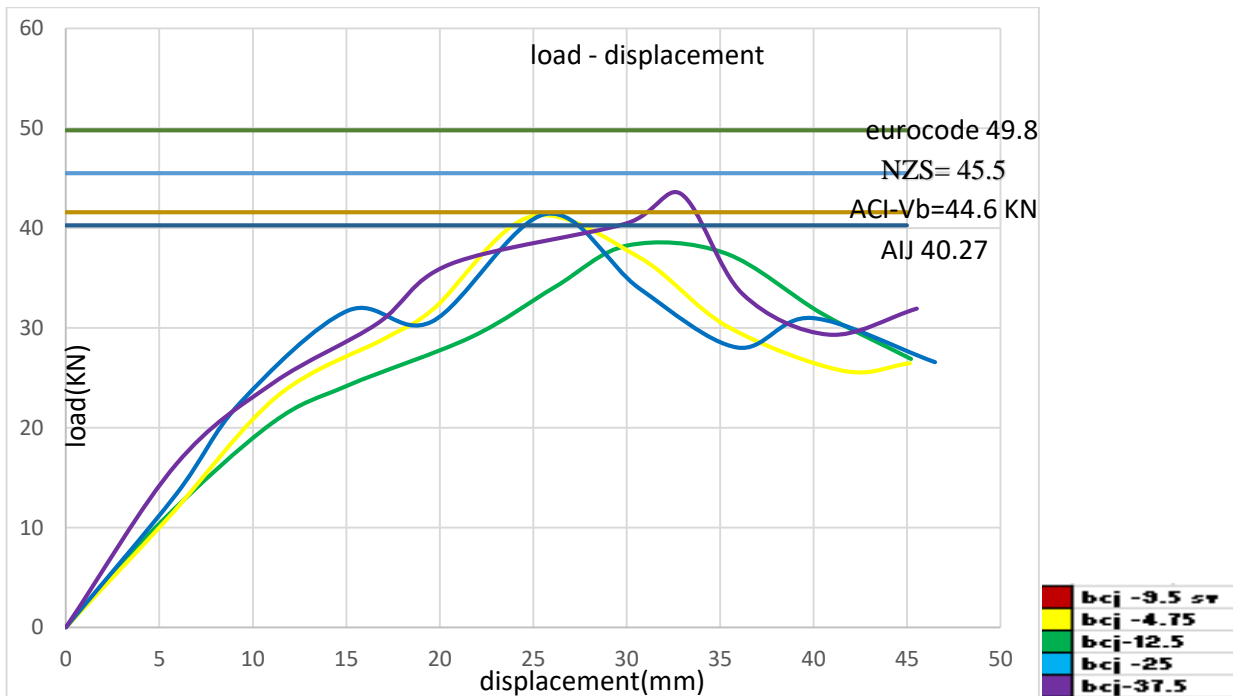


Figure 4.16 Comparison between Code equations with experimental results.

It can be seen from figure 4:17 ACI Code and Japanese Code more or less similar prediction. Whereas Euro Code (EC) resistance prediction is higher than ACI Code and Japanese Code

Summary of results for the Margin of Safety (V_{exp}/V_{pre}) of empirical equations used in different Codes for predicting the joint shear capacity of external beam column joint.

Table 4.1 Margin of Safety (V_{exp}/V_{pre}) of empirical equations used in different Codes for predicting the joint shear capacity of beam column joint

Code	Margin of Safety				
	Bcj-9.5-sv	Bcj-4.75	Bcj-12.5	Bcj-25	Bcj-37.5
AIJ(Japanese)	0.79	0.93	1.02	1.03	1.08
ACI	0.72	0.86	0.93	0.93	0.98
NZS	0.70	0.84	0.91	0.91	0.96
EC	0.64	0.77	0.83	0.83	0.87

All three codes (AIJ, ACI, and EC) recognize that the shear strength of a beam-column joint is influenced by the concrete's compressive strength, the joint's configuration, and its area. However, when reinforcement within the joint becomes highly congested, the ideal composition of the concrete core assumed by these codes may not be achieved. In severely congested joints, such as specimen (Bcj-9.5-sv) where only mortar could effectively pass through the dense reinforcement, the actual joint shear strength significantly underperformed the code predictions, reaching only 79% of the AIJ standard, 72% of the ACI standard, and 64% of the EC prediction. Similarly specimen Bcj-4.75($a_{gmax} = 4.75\text{mm}$) The joint shear resistance was approximately 93% (AIJ), 86% (ACI), and 77% (EC) of what was achieved by Bcj-37.5, indicating reductions of 15%, 12%, and 10%, respectively, based on these code, suggesting that adequate aggregate interlock within the joint is crucial for achieving the intended shear capacity as per code provisions.

When dealing with congested beam-column joints, smaller aggregate (Bcj-4.75) proves more beneficial than larger aggregate (Bcj-9.5-sv). This is because the larger aggregate can't effectively penetrate the core concrete, altering the mix to a mortar-like consistency in Bcj-9.5-sv applications. To mitigate reinforcement congestion in beam-column joints, design strategies include increasing member size for better spacing, optimizing the layout of reinforcing bars by staggering splices, utilizing smaller diameter bars, considering headed reinforcement to reduce development length, and incorporating steel fibers to enhance shear resistance and confinement. During construction,

proper detailing in drawings is crucial, along with phased installation in highly congested areas, and the use of templates and spacers to maintain accurate reinforcement placement and alignment.

Self-Consolidating Concrete (SCC) offers superior flow compared to conventional concrete, enabling it to easily fill congested spaces without extensive vibration. This characteristic is crucial for preventing voids and ensuring proper bonding with steel reinforcement. An experimental study focused on evaluating the structural performance of Self-Compacting Concrete (SCC) against traditionally vibrated concrete (VC) in beams with closely spaced reinforcement. The investigation considered failure modes, ultimate strength, deflection behavior, cracking patterns, and calculated moment capacities. While both types of concrete beams experienced flexural failure, SCC demonstrated clear advantages. Specifically, SCC beams exhibited a 10% greater ultimate load-carrying capacity than the referenced VC beams in these reinforcement-congested elements. Additionally, experimental results showed a higher factor of safety relative to theoretical predictions for SCC beams, with an average ratio of experimental to theoretical ultimate moments of 1.46, exceeding the 1.36 ratio observed in VC beams. This suggests that SCC is particularly beneficial in densely reinforced structural members (Abrham and Asnake, 2020)

CHAPTER 5 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Research on congested beam-column joints, vital for earthquake-prone areas like Addis Ababa, reveals that both aggregate size and volume significantly affect their shear performance. The experimental investigation involving five exterior beam-column joint specimens, demonstrated that aggregate size has a substantial impact on joint behavior. Specifically, it was found that smaller aggregates led to a 12% reduction in beam-column joint resistance when compared to the maximum aggregate size of 37.5 mm down to 4.75 mm. Moreover, the study revealed that aggregate volume also plays a critical role, with an approximately 26% decrease in joint shear capacity observed in our experiments. These findings underscore the need to consider both aggregate size and volume in future research and potential updates to building codes, which is vital for ensuring structural integrity in regions susceptible to seismic activity. Additionally, the research indicated that larger aggregates contributed to a more favorable ductile failure mode, contrasting with the brittle failure observed with smaller aggregates, reinforcing existing knowledge that larger aggregates generally enhance joint shear capacity and improve post-peak behavior.

The size of the aggregate within a concrete mix significantly influences the characteristics of crack formation and propagation under stress. Larger aggregates tend to produce wider shear cracks, although fewer in number. This is attributed to the increased roughness of the crack surfaces created by larger aggregates, which enhances the transfer of shear stresses across the crack. Conversely, smaller aggregates lead to the development of narrower cracks, but these occur more frequently throughout the beam column joint.

Furthermore, the size of the aggregate plays a vital role in the energy dissipation capacity of concrete. Generally, larger aggregate sizes result in higher energy dissipation. Significant decrease on energy dissipation capacity about 21% from Bcj-37.5 to Bcj-9.5-sv, and 11.60% reduction between Bcj-37.5 and Bcj-4.75. This is primarily due to the increased fracturing of the aggregates when the concrete is subjected to load. This fracturing process, particularly pronounced with larger aggregates, enables the concrete to absorb and dissipate more energy.

These findings highlight the importance of considering aggregate size in future research and potentially in revisions to building codes, especially in regions prone to ground shaking, where structural integrity is paramount. Although current building codes might not explicitly address aggregate size in shear capacity calculations, our results, in conjunction with prior evidence, strongly suggest its relevance, pointing towards a requirement for a more refined approach beyond general recommendations for aggregate size.

5.2 Recommendation

Building codes should consider the effect of aggregate size in the prediction of the shear capacity of beam-column joints. To maximize shear capacity while adhering to code limitations and avoiding congestion, the possible maximum aggregate size should be utilized. Furthermore, as the shear resistance behavior of beam-column joints is influenced by various factors, future research should expand upon this study to explore the effect of aggregate size in relation to other parameters such as aggregate type, shape, and concrete grade. Lastly, it is noted that the manual loading applied in this study due to equipment limitations might have affected accuracy, and the availability of an automatic displacement control machine could potentially yield more precise predictions in future investigations.

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Appendix

Appendix A - Tests for Fine Aggregate

Appendix B - Tests for Coarse Aggregate

Appendix C - Mix Design

Appendix, A - Tests for Fine Aggregate

Table A-1 sieve analysis for fine aggregate

Sieve Size (mm)	Retained Weight	Retained Percent	Cumulative Retained (%)	Cumulative Pass (%)	ASTMC 33 Passing Standard
4.75	0.04	4.00	4.00	96.00	95-100
2.36	0.1	10.00	14.00	86.00	80-100
1.18	0.34	25.00	39.00	62.00	55-85
0.6	0.36	36.50	75.50	24.50	25-60
0.3	0.20	20.00	95.50	4.50	5-30
0.15	0.03	3.00	98.50	1.50	0-10
pan	0.02	1.50	100.00	0.00	0

$$\begin{aligned} \text{Fineness modulus} &= \sum(\text{cumulative percent retained}/100) \\ &= 326.5/100 \\ &= 3.26 \end{aligned}$$

A-1 Moisture content of fine aggregate

Weight of original sample = 2565g

Weight of original sample + weight of container=3106.9g

Weight of container =541.9g

Weight of oven-dry sample and container =3065.8g

Moisture content

$$\begin{aligned} &= \frac{\text{Original sample weight} - (\text{oven dry weight} - \text{Weight of container}) * 100}{(\text{oven} - \text{dry weight})} \\ &= \frac{852.2 - (1460.7-647.7)}{1460.7 - 647.7} \\ &= 4.83\% \end{aligned}$$

A-2 Specific gravity for fine aggregate

Bulk specific gravity of fine aggregate = 1521.7kg/m³

Weight of original sample = 500g (*S*)

Weight of water+ weight of pycnometer = 706.7g (*B*)

Weight of sample+ water+ pycnometer = 1000.1g (*C*)

Weight of oven-dry sample =472.6g (*A*)

$$\text{Bulk specific gravity} = \frac{A}{(B+S-C)} = \frac{472.6}{(706.7+500-1000.1)} = 2.29$$

$$\text{Bulk specific gravity (SSD basis)} = \frac{S}{(B+S-C)} \frac{500}{(706.7+500-1000.1)} = 2.42$$

$$\text{Apparent specific gravity} = \frac{A}{(B+A-C)} \frac{472.6}{(706.7+472.6-1000.1)} = 2.63$$

$$\text{Absorption capacity} = \frac{S-A}{A} = \frac{500-472.6}{472.6} = 5.79\%$$

Appendix B - Tests for Coarse Aggregate

B-1: Moisture content of coarse aggregate 37.5

Bulk unit weight = 1599.5 kg/m³

Weight of original sample = 2517.5 g

Weight of container = 500 g

Weight of oven-dry sample = 2989.7 g

Moisture content

$$\begin{aligned} &= \frac{\text{Original sample weight} - (\text{oven dry weight} - \text{Weight of container}) * 100}{(\text{oven} - \text{dry weight})} \\ &= \frac{2517.5 - (2989.7 - 500) * 100}{2989.7 - 500} \\ &= 1.116\% \end{aligned}$$

B-2: Specific gravity for coarse aggregate

Measurement Oven Dry (OD), Wt. of Sample = 4879.3 g (A) 1988.2

Measurement in the air (SSD), Wt. of Sample = 4975 g (B) 2031

Measurement soaked in water (Submerged), Wt. of Sample = 1226.7 g (C)

$$\text{Relative Density (Specific Gravity) OD} = \frac{A}{B-C} = \frac{1988.2}{2031-1226.7} = 2.47$$

$$\text{Relative Density (Specific Gravity) SSD} = \frac{B}{B-C} = \frac{2031}{2031-1226.7} = 2.53$$

$$\text{Apparent Specific Gravity} = \frac{A}{A-C} = \frac{1988.2}{1988.2-1226.7} = 2.61$$

$$\text{Absorption Capacity (\%)} = \frac{B-A}{A} = \frac{2031-1988.2}{1988.2} = 2.51\%$$

Table B-1 Summary of material properties

No	Test Description	Cement	Coarse aggregate of each size (mm)				Fine aggregate
			37.5	25	12.5	4.75	
1	Specific Gravity	3.15					
2	Bulk Density		1599	1588	1592	1847	1521
3	Moisture content:		1.11	1.37	1.98	1.56	1.62
4	Water absorption		2.15	2.03	3.14	1.61	4.10
5	Bulk Specific Gravity (SSD basis)		2.53	2.50	2.50	1.58	3.80
6	Silt content						2.00
7	Fineness Modulus						3.26

Appendix C - Mix Design

Trail Mix- Design Using ACI Methods for Conventional Concrete (C-25 with a maximum size of aggregate=37.5mm).

Materials properties:-

Concrete with compressive strength of 25Mpa (C-25) is required to be produced

- From materials quality test we have the following result.

a) cement; type 1; specific gravity= 3.15

b) coarse aggregates:

✓ bulk specific gravity=2.53

✓ absorption capacity=2.15%

✓ moisture content=1.116%

✓ compacted unit weight=1599.5KN/m³

c) fine aggregate (sand)

✓ bulk specific gravity=2.43

✓ absorption capacity= 5.79%

✓ moisture content = 4.83%

✓ fines modulus=3.00

The mix design procedures are as follows:-

1. Choice of slump

Table C-1 Recommended slumps for various types of construction (ACI-2111-91)

Types of construction	Maximum Slump (mm)	Minimum Slump (mm)
Reinforced foundation walls and footings	75	25
Plain footings, caissons, and substructure walls	75	25
Beams and reinforced walls	100	25
Building columns	100	25
Pavements and slabs	75	25
Mass concrete	75	25

From table

1. Assume that a type of construction is beams and building column.

This implies, maximum slump= 100mm and minimum slump= 25mm.

2. maximum size of aggregates sand or fine aggregates =
4.75mm and course aggregates =37.5mm
3. Estimation of mixing water and air content

Assume non air entrained concrete

Table C-2 Approximate Mixing Water and Air Content Requirements for Different Slumps and Nominal Maximum Sizes of Aggregates (ACI-2111-91)

NON-AIR-ENTRAINED CONCRETE								
Slump (mm)	9.5 mm	12.5 mm	19 mm	25 mm	37.5mm	50 mm	75 mm	150 mm
25 to 50	207	199	190	179	166	154	130	113
75 to 100	228	216	205	193	181	169	145	124
150 to 175	243	228	216	202	190	178	160	-
> 175	-	-	-	-	-	-	-	-

Approximate amount of entrapped air in non-air-entrained concrete (%)								
Slump (mm)	9.5 mm	12.5 mm	19 mm	25 mm	37.5mm	50 mm	75 mm	150 mm
All	3.0	2.5	2.0	1.5	1.0	0.5	0.3	0.2

From table C-2 of ACI standards, for non-air entrained and slump of 75-100, the water in 1m³ of concrete is 181Kg.

4. Water to cement ratio selection table 3

Table C-3 Relationship between water-cement or water-cementations materials ratio and compressive strength of concrete (ACI-2111-91)

Compressive strength at 28 days (MPa)	Water-cement ratio by weight (Non-air-entrained concrete)
40	0.42
35	0.47
30	0.54
25	0.61
20	0.69
15	0.79

From table C-3, for C-25MPa and non-air entrained concrete water to cement ratio is 0.61

5. Cement content calculation

For slump of 75-100

Water content=181Kg/m³

Water/cement=0.57

Cement content = $water\ content / (\frac{w}{c}) = \frac{181}{0.57} = 317.5\text{kg}$

6. Estimation of coarse aggregates content (Table C-4)

Table C-4 Volume of oven-dry-rodded coarse aggregate per unit volume of concrete for different fineness moduli of fine aggregate. (ACI-2111-91)

Nominal maximum size of aggregate (mm)	2.40	2.60	2.80	3.00
9.5	0.50	0.48	0.46	0.44
12.5	0.59	0.57	0.55	0.53
19	0.66	0.64	0.62	0.60
25	0.71	0.69	0.67	0.65
37.5	0.75	0.73	0.71	0.69
50	0.78	0.76	0.74	0.72
75	0.82	0.80	0.78	0.76
150	0.87	0.85	0.83	0.81

From table C- 4 of ACI, for maximum size of aggregate= 37.5mm and fines modules for sand = 3.00, the volume of coarse aggregate per unit volume of concrete is

$$= 0.69$$

$$required\ dry\ mass\ of\ C.\ A = 0.69 * 1599.5$$

$$= 1103.655\text{kg/m}^3$$

7. Estimation of fine aggregates content

At the end of Step 6, all ingredients of the concrete have been estimated except the fine aggregate. Its quantity is determined by difference. Either of the two procedures may be employed:

- The weight method or
- The absolute volume method

If the weight of the concrete per unit volume is assumed or can be estimated from experience, the required weight of fine aggregate is simply the difference between the weight of fresh concrete and the total weight of the other ingredients. Therefore, in this paper the weight method preferred.

➤ **Content of fine aggregate (F.A) = unit weight of concrete – (C.A + cement + water)**

First estimate the unit weight of fresh concretes from Table C-5.

Table C-5 First estimate of concrete weight (kg/m^3)

Nominal maximum size of aggregate (mm)	Non-air-entrained concrete (kg/m^3)
9.5	2280
12.5	2310
19	2345
25	2380
37.5	2410
50	2445
75	2490
150	2530

From the table C-5 the unit weight of fresh concrete corresponding to max. Aggregate size of 37.5mm and non- air entrained is **2410kg/m³**.

$$\text{Fine aggregate content} = [2410 - (1103.65+317.54+181)] = \underline{\underline{807.81\text{kg/m}^3}}$$

8. Moisture adjustment

Absorbed water does not become part of the mixing water and it must be removed from the mixing water, if moisture content is greater than absorption capacity. But, if absorption capacity is greater than moisture content of aggregate, we need to add water up to its moisture capacity. Therefore, in this case since the absorption capacity of the aggregates are greater than their moisture content, water should be added from the mixing water.

$$\text{Additional water from C.A} = 2.15-1.116 = \mathbf{1.034\%}$$

$$\text{Additional water from F.A} = 5.79-4.83 = \mathbf{0.96\%}$$

$$\text{Total water required} = 181+1103.65*0.01034+807.81*0.0096$$

$$= \mathbf{200.16\text{kg/ m}^3}$$

Table C-6 the estimated ingredients for a meter cube of concrete is therefore, summarized as follows.

Ingredients	Weight per m³ (kg/m³)
Course aggregate	1103.5
Fine aggregate	807.81
Cement	317.54
Water	200.16
Conc. Unit weight	2408.191

9. Trial batch

12 sample are needed 6 for compressive strength 150x150x150 and 6 for tensile strength test 150mm diameter and 300mm height = $0.06594m^3$

Beam-column joint Concrete volume = $0.3*0.3*0.2=0.018$

Sub Total= $0.06594+0.018=0.084m^3$

Considering 5% waste = $0.0042m^3$

$V_{total}=0.084+0.0042= \mathbf{0.0882m^3}$

Table C-7 Ingredients for the trail batch

Ingredients	Weight per $m^3(kg/m^3)$
Course aggregate	97.3
Fine aggregate	71.2
Cement	28
Water	17.66

Trail Mix- Design Using ACI Methods for Conventional Concrete (C25 with a Maximum size of aggregate=25mm).

Materials properties:-

Concrete with compressive strength of 25MPa (C-25) is required to be produced

- From materials quality test we have the following result.

a) cement; type 1; specific gravity= 3.15

b) course aggregates:

✓ bulk specific gravity=2.506

✓ absorption capacity=2.03%

- ✓ moisture content=1.377%
- ✓ compacted unit weight=1588.65KN/m³

c) fine aggregate (sand)

- ✓ bulk specific gravity=2.43
- ✓ absorption capacity= 5.79%
- ✓ moisture content = 4.83%
- ✓ fines modulus=3.00

The mix design procedures are as follows:-

1. Choice of slump

Table C-8 Recommended slumps for various types of construction (ACI-2111-91)

Types of construction	Maximum Slump (mm)	Minimum Slump (mm)
Reinforced foundation walls and footings	75	25
Plain footings, caissons, and substructure walls	75	25
Beams and reinforced walls	100	25
Building columns	100	25
Pavements and slabs	75	25
Mass concrete	75	25

From table

1. Assume that a type of construction is beams and building column.

This implies, maximum slump= 100mm and minimum slump= 25mm.

2. maximum size of aggregates sand or fine aggregates = 4.75mm and coarse aggregates =37.5mm
3. Estimation of mixing water and air content

Assume non air entrained concrete

Table C-9 Approximate Mixing Water and Air Content Requirements for Different Slumps and Nominal Maximum Sizes of Aggregates (ACI-2111-91)

NON-AIR-ENTRAINED CONCRETE								
Slump (mm)	9.5 mm	12.5 mm	19 mm	25 mm	37.5mm	50 mm	75 mm	150 mm
25 to 50	207	199	190	179	166	154	130	113
75 to 100	228	216	205	193	181	169	145	124
150 to 175	243	228	216	202	190	178	160	-
> 175	-	-	-	-	-	-	-	-

Approximate amount of entrapped air in non-air-entrained concrete (%)								
Slump (mm)	9.5 mm	12.5 mm	19 mm	25 mm	37.5mm	50 mm	75 mm	150 mm
All	3.0	2.5	2.0	1.5	1.0	0.5	0.3	0.2

From table C-9 of ACI standards, for non-air entrained and slump of 75-100, the water in 1m³ of concrete is 193Kg.

4. Water to cement ratio selection Table C-10

Table C-10 Relationship between water-cement or water-cementations materials ratio and compressive strength of concrete (ACI-2111_91)

Compressive strength at 28 days (MPa)	Water-cement ratio by weight (Non-air-entrained concrete)
40	0.42
35	0.47
30	0.54
25	0.61
20	0.69

15

0.79

From table C-10, for C-25 and non-air entrained concrete water to cement ratio is 0.61

5. Cement content calculation

For slump of 75-100

Water content = 193Kg/m³

Water/cement = 0.57

Cement content = $\text{water content} / \left(\frac{w}{c}\right) = \frac{193}{0.57} = 338.6\text{kg}$

6. Estimation of course aggregates content (Table C-11)

Table C-11 Volume of oven-dry-rodded coarse aggregate per unit volume of concrete for different fineness moduli of fine aggregate. (ACI-2111-91)

Nominal maximum size of aggregate (mm)	2.40	2.60	2.80	3.00
9.5	0.50	0.48	0.46	0.44
12.5	0.59	0.57	0.55	0.53
19	0.66	0.64	0.62	0.60
25	0.71	0.69	0.67	0.65
37.5	0.75	0.73	0.71	0.69
50	0.78	0.76	0.74	0.72
75	0.82	0.80	0.78	0.76
150	0.87	0.85	0.83	0.81

From table C-11 of ACI, for maximum size of aggregate = 25mm and fines modules for sand = 3.00, the volume of course aggregate per unit volume of concrete is

$$= 0.65$$

$$\begin{aligned} \text{required dry mass of } C.A &= 0.65 * 1588.65 \\ &= 1032.62 \text{ kg/m}^3 \end{aligned}$$

7. Estimation of fine aggregates content

At the end of Step 6, all ingredients of the concrete have been estimated except the fine aggregate. Its quantity is determined by difference. Either of the two procedures may be employed:

- The weight method or
- The absolute volume method

If the weight of the concrete per unit volume is assumed or can be estimated from experience, the required weight of fine aggregate is simply the difference between the weight of fresh concrete and the total weight of the other ingredients. Therefore, In this paper the weight method preferred.

- **Content of fine aggregate (F.A) = unit weight of concrete – (C.A + cement + water)**

First estimate the unit weight of fresh concretes from Table C-12.

Table C-12 First estimate of concrete weight (kg/m^3)

Nominal maximum size of aggregate (mm)	Non-air-entrained concrete (kg/m^3)
9.5	2280
12.5	2310
19	2345
25	2380
37.5	2410
50	2445
75	2490
150	2530

From the table C-12 the unit weight of fresh concrete corresponding to max. Aggregate size of 37.5mm and non- air entrained is **2380kg/m³**.

$$\text{Fine aggregate content} = [2380 - (1032.62+338.6+193)] = \underline{\underline{815.78\text{kg/m}^3}}$$

8. Moisture adjustment

Absorbed water does not become part of the mixing water and it must be removed from the mixing water, if moisture content is greater than absorption capacity. But, if absorption capacity is greater than moisture content of aggregate, we need to add water up to its moisture capacity. Therefore, in this case since the absorption capacity of the aggregates are greater than their moisture content, water should be added from the mixing water.

$$\text{Additional water from C.A} = 2.03-1.377 = \underline{\underline{0.653\%}}$$

$$\text{Additional water from F.A} = 5.79-4.83 = \underline{\underline{0.96\%}}$$

$$\begin{aligned} \text{Total water required} &= 193+1032.62*0.00653+815.78*0.0096 \\ &= \underline{\underline{207.57 \text{ kg/m}^3}} \end{aligned}$$

Table C-13 the estimated ingredients for a meter cube of concrete is therefore, summarized as follows.

Ingredients	Weight per m³ (kg/m³)
Course aggregate	1032.62
Fine aggregate	815.78
Cement	338.6
Water	207.57
concrete Unit weight	2394.78

9. Trial batch

12 samples are needed 6 for tensile strength 100mm diameter and 200mm height and 6 for compressive strength test 150x150x150mm size=0.04121m³

Beam-column Concrete volume = $3.65 \times 0.2 \times 0.3 \times 5 = 1.095$

Sub Total=0.04121+1.095m³ = 1.14

Considering 5% waste = 0.057m³

$V_{\text{total}} = 1.14 + 0.057 = \mathbf{1.197m^3}$

Table C-14 Ingredients for the trail batch

Ingredients	Weight per m³ (kg/m³)
Course aggregate	1236.04
Fine aggregate	976.48
Cement	405.30
Water	248.40

Trail Mix- Design Using ACI Methods for Conventional Concrete (C25 with a Maximum size of aggregate=12.5mm).

Materials properties:-

Concrete with compressive strength of 25Mpa (C-25) is required to be produced

- From materials quality test we have the following result.

a) Cement; type 1; specific gravity= 3.15

b) course aggregates:

✓ bulk specific gravity=2.5

✓ absorption capacity=3.14%

- ✓ moisture content=1.985%
- ✓ compacted unit weight=1592.2KN/m³

c) fine aggregate (sand)

- ✓ bulk specific gravity=2.43
- ✓ absorption capacity= 5.79%
- ✓ moisture content = 4.83%
- ✓ fines modulus=3.00

The mix design procedures are as follows:-

1. Choice of slump

Table C-15 Recommended slumps for various types of construction (ACI-2111-91)

Types of construction	Maximum Slump(mm)	Minimum Slump(mm)
Reinforced foundation walls and footings	75	25
Plain footings, caissons, and substructure walls	75	25
Beams and reinforced walls	100	25
Building columns	100	25
Pavements and slabs	75	25
Mass concrete	75	25

From table

1. Assume that a type of construction is beams and building column.

This implies, maximum slump= 100mm and minimum slump= 25mm.

2. maximum size of aggregates sand or fine aggregates = 4.75mm and course aggregates =37.5mm

3. Estimation of mixing water and air content

Assume non air entrained concrete

Table C-16 Approximate Mixing Water and Air Content Requirements for Different Slumps and Nominal Maximum Sizes of Aggregates (ACI-2111-91)

NON-AIR-ENTRAINED CONCRETE								
Slump (mm)	9.5 mm	12.5 mm	19 mm	25 mm	37.5mm	50 mm	75 mm	150 mm
25 to 50	207	199	190	179	166	154	130	113
75 to 100	228	216	205	193	181	169	145	124
150 to 175	243	228	216	202	190	178	160	-
> 175	-	-	-	-	-	-	-	-

Approximate amount of entrapped air in non-air-entrained concrete (%)								
Slump (mm)	9.5 mm	12.5 mm	19 mm	25 mm	37.5mm	50 mm	75 mm	150 mm
All	3.0	2.5	2.0	1.5	1.0	0.5	0.3	0.2

From table C-16 of ACI standards, for non-air entrained and slump of 75-100, the water in 1m³ of concrete is **216Kg**.

3. Water to cement ratio selection from Table C-17

Table C-17 Relationship between water-cement or water-cementations materials ratio and compressive strength of concrete (ACI-2111-91)

Compressive strength at 28 days (MPa)	Water-cement ratio by weight (Non-air-entrained concrete)
40	0.42
35	0.47
30	0.54
25	0.61
20	0.69
15	0.79

From table C-17, for C-25 and non-air entrained concrete water to cement ratio is 0.61

5, Cement content calculation

For slump of 75-100

Water content=216Kg/m³

Water/cement=0.61

Cement content= $\text{water content} / \left(\frac{w}{c}\right) = \frac{216}{0.61} = 354.1 \text{kg}$

6, Estimation of course aggregates content (Table C-18)

Table C-18 Volume of oven-dry-rodded coarse aggregate per unit volume of concrete for different fineness moduli of fine aggregate.(ACI-2111-91)

Nominal maximum size of aggregate (mm)	2.40	2.60	2.80	3.00
9.5	0.50	0.48	0.46	0.44
12.5	0.59	0.57	0.55	0.53
19	0.66	0.64	0.62	0.60
25	0.71	0.69	0.67	0.65
37.5	0.75	0.73	0.71	0.69
50	0.78	0.76	0.74	0.72
75	0.82	0.80	0.78	0.76
150	0.87	0.85	0.83	0.81

From Table C-18 of ACI, for maximum size of aggregate= 12.5mm and fines modules for sand = 3.00, the volume of course aggregate per unit volume of concrete is = 0.53

$$\text{required dry mass of } C. A = 0.53 * 1592.2$$

$$= 843.86\text{kg}$$

7. Estimation of fine aggregates content

At the end of Step 6, all ingredients of the concrete have been estimated except the fine aggregate. Its quantity is determined by difference. Either of the two procedures may be employed:

- The weight method or
- The absolute volume method

If the weight of the concrete per unit volume is assumed or can be estimated from experience, the required weight of fine aggregate is simply the difference between the weight of fresh

concrete and the total weight of the other ingredients. Therefore, In this paper the weight method preferred.

➤ **Content of fine aggregate (F.A) = unit weight of concrete – (C.A + cement + water)**

First estimate the unit weight of fresh concretes from Table C-19

Table C-19 First estimate of concrete weight (kg/m³)

Ingredients	Weight per m³ (kg/m³)
Course aggregate	1032.62
Fine aggregate	815.78
Cement	338.6
Water	207.57
concrete Unit weight	2394.78

From the Table C-19 the unit weight of fresh concrete corresponding to max. Aggregate size of 37.5mm and non- air entrained is **2310kg/m³**.

Fine aggregate content = [2310 – (843.86+378.9+216)] = **871.24kg/m³**

8. Moisture adjustment

Absorbed water does not become part of the mixing water and it must be removed from the mixing water, if moisture content is greater than absorption capacity. But, if absorption capacity is greater than moisture content of aggregate, we need to add water up to its moisture capacity. Therefore, in this case since the absorption capacity of the aggregates are greater than their moisture content, water should be added from the mixing water.

Additional water from C.A = 3.14-1.985 = **1.155%**

Additional water from F.A = 5.79-4.83 = **0.96%**

Total water required = $216+843.86*0.01155+871.24*0.0096 = 234.11\text{kg/m}^3$

Table C-20 the estimated ingredients for a meter cube of concrete is therefore, summarize.

Ingredients	Weight per m ³ (kg/m ³)
Course aggregate	843.86
Fine aggregate	871.24
Cement	378.9
Water	234.11
Conc. Unit weight	2328.11

9. Trial batch

12 samples are needed 6 for tensile strength 100mm diameter and 200mm height and 6 for compressive strength test 150x150x150mm size=0.04121m³

Beam-column Concrete volume = $0.3*0.2*0.3= 0.018$

Sub Total= $0.04121+0.0.018\text{m}^3 =0.05921$

Considering 5% waste = 0.00296 m^3

$V_{\text{total}} =0.05921+0.00296= 0.06217 \text{ m}^3$

Table C-21 Ingredients for the trail batch

Ingredients	Weight per m ³ (kg/m ³)
Course aggregate	52.46
Fine aggregate	54.16
Cement	23.55
Water	14.55

Trail Mix- Design Using ACI Methods for Conventional Concrete (C25 with a maximum size of aggregate=4.75mm).

Materials properties:-

Concrete with compressive strength of 25Mpa (C-25) is required to be produced

- From materials quality test we have the following result.

a) Cement; type 1; specific gravity= 3.15

b) Course aggregates:

- ✓ bulk specific gravity=2.5
- ✓ absorption capacity=2.35%
- ✓ moisture content=1.31%
- ✓ compacted unit weight=1846.9KN/m³

c) Fine aggregate (sand)

- ✓ bulk specific gravity=2.43
- ✓ absorption capacity= 5.79%
- ✓ moisture content = 4.83%
- ✓ fines modulus=3.00

The mix design procedures are as follows:-

1. Choice of slump

Table C-22 Recommended slumps for various types of construction (ACI-2111-91)

Types of construction	Maximum Slump(mm)	Minimum Slump(mm)
Reinforced foundation walls and footings	75	25
Plain footings, caissons, and substructure walls	75	25
Beams and reinforced walls	100	25
Building columns	100	25
Pavements and slabs	75	25
Mass concrete	75	25

From table

1. Assume that a type of construction is beams and building column.

This implies, maximum slump= 100mm and minimum slump= 25mm.

2. maximum size of aggregates sand or fine aggregates = 4.75mm and course aggregates =37.5mm
3. Estimation of mixing water and air content

Assume non air entrained concrete

Table C-23 Approximate Mixing Water and Air Content Requirements for Different Slumps and Nominal Maximum Sizes of Aggregates (ACI-2111-91)

NON-AIR-ENTRAINED CONCRETE								
Slump (mm)	9.5 mm	12.5 mm	19 mm	25 mm	37.5mm	50 mm	75 mm	150 mm
25 to 50	207	199	190	179	166	154	130	113
75 to 100	228	216	205	193	181	169	145	124
150 to 175	243	228	216	202	190	178	160	-
> 175	-	-	-	-	-	-	-	-

Approximate amount of entrapped air in non-air-entrained concrete (%)								
Slump (mm)	9.5 mm	12.5 mm	19 mm	25 mm	37.5mm	50 mm	75 mm	150 mm
All	3.0	2.5	2.0	1.5	1.0	0.5	0.3	0.2

From table C-23 of ACI standards, for non-air entrained and slump of 75-100, the water in 1m³ of concrete is **236.75Kg**.

4. Water to cement ratio selection Table C-24

Table C-24 Relationship between water-cement or water-cementations materials ratio and compressive strength of concrete (ACI-2111-91)

Compressive strength at 28 days (MPa)	Water-cement ratio by weight (Non-air-entrained concrete)
40	0.42
35	0.47
30	0.54
25	0.61
20	0.69
15	0.79

From Table C-24, for C-25 and non-air entrained concrete water to cement ratio is 0.61

5, Cement content calculation

For slump of 75-100

Water content=236.75Kg/m³

Water/cement=0.61

Cement content= $\text{water content} / \left(\frac{w}{c}\right) = \frac{236.75}{0.61} = 415.35\text{kg}$

6, Estimation of course aggregates content (table 4)

Table C-25 Volume of oven-dry-rodded coarse aggregate per unit volume of concrete for different fineness moduli of fine aggregate. (ACI-2111-91)

Nominal maximum size of aggregate (mm)	2.40	2.60	2.80	3.00
9.5	0.50	0.48	0.46	0.44
12.5	0.59	0.57	0.55	0.53
19	0.66	0.64	0.62	0.60
25	0.71	0.69	0.67	0.65
37.5	0.75	0.73	0.71	0.69
50	0.78	0.76	0.74	0.72
75	0.82	0.80	0.78	0.76
150	0.87	0.85	0.83	0.81

From table C-25 of ACI, for maximum size of aggregate= 4.75mm and fines modules for sand = 3.0 and the volume of course aggregate per unit volume of concrete is

$$= 0.234$$

$$\text{required dry mass of } C. A = 0.234 * 1846.9$$

$$= 432.17\text{kg}$$

7. Estimation of fine aggregates content

At the end of Step 6, all ingredients of the concrete have been estimated except the fine aggregate. Its quantity is determined by difference. Either of the two procedures may be employed:

- The weight method or
- The absolute volume method

If the weight of the concrete per unit volume is assumed or can be estimated from experience, the required weight of fine aggregate is simply the difference between the weight of fresh

concrete and the total weight of the other ingredients. Therefore, In this paper the weight method preferred.

➤ **Content of fine aggregate (F.A) = unit weight of concrete – (C.A + cement + water)**

Table C-26 First estimate of concrete weight (kg/m³)

Nominal maximum size of aggregate (mm)	Non-air-entrained concrete (kg/m ³)
9.5	2280
12.5	2310
19	2345
25	2380
37.5	2410
50	2445
75	2490
150	2530

From the Table C-26 the unit weight of fresh concrete corresponding to max. Aggregate size of 37.5mm and non- air entrained is **2232.5kg/m³**.

Fine aggregate content = [2232.5 – (432.17+415.35+236.75)] = **1148.23kg/m³**

8. Moisture adjustment

Absorbed water does not become part of the mixing water and it must be removed from the mixing water, if moisture content is greater than absorption capacity. But, if absorption capacity is greater than moisture content of aggregate, we need to add water up to its moisture capacity. Therefore, in this case since the absorption capacity of the aggregates are greater than their moisture content, water should be added from the mixing water.

Additional water from C.A = 2.35-1.31 = **1.04%**

Additional water from F.A = $5.79 - 4.83 = 0.96\%$

Total water required = $236.75 + 432.17 * 0.0104 + 1148.23 * 0.0096$

$$= 252.26 \text{ kg/m}^3$$

Table C-27 the estimated ingredients for a meter cube of concrete is, summarized as follows.

Ingredients	Weight per m ³ (kg/m ³)
Course aggregate	432.17
Fine aggregate	1148.23
Cement	415.35
Water	252.26
Conc. Unit weight	2248.01

9. Trial batch

12 Cylinders are needed of 6 for compressive strength 100mm diameter and 200mm height and 6 for tensile strength test 150mm diameter and 300mm height = 0.04121 m^3

Beam-column Concrete volume = $0.3 * 0.2 * 0.3 = 0.018$

Sub Total = $0.04121 + 0.018 \text{ m}^3 = 0.05921$

Considering 5% waste = 0.00296 m^3

$V_{\text{total}} = 0.05921 + 0.00296 = 0.06217 \text{ m}^3$

Table C-28 Ingredients for the trial batch

Ingredients	Weight per m³ (kg/m³)
Course aggregate	26.86
Fine aggregate	71.38
Cement	25.86
Water	15.68