



Palestine Polytechnic University  
Deanship of Graduate Studies and Scientific Research  
College of Civil Engineering- Structural Engineering

**Utilizing Recycled Glass as Partial and Total Replacement of Fine  
Aggregate in Structural Concrete**

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Thesis submitted in partial fulfillment of the requirements of the degree of Master of  
Science in civil engineering to the faculty of Graduate Studies at Palestine  
Polytechnic University

May - 2026

**Master of Engineering Program**

The undersigned hereby certify that they have read, examined and recommended the thesis referred to below to the Deanship of Graduate Studies and Scientific Research at Palestine Polytechnic University

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**By: Mazen Ahmed Ibrahim Mahani**

**In partial fulfillment of the requirements for the degree of Master in Civil Engineering- Structural Engineering.**

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## DEDICATION

To those who ignited our curiosity and through it, guided our thinking to seek, to question, and ultimately to discover...

To those who, with their wisdom, turned every problem into a lesson and every single doubt into a path for growth and development...

To the mentors and teachers who did not only pass on knowledge but also shaped our character and inspired us to go beyond even the limits we once thought unbreakable

To my dear wife, the partner of my journey, and my beloved children, who have been my sanctuary and source of strength, brightening the longest days with their patience, warmth, and unwavering belief in me

To my family, whose constant love, patience, and unwavering support helped me overcome the toughest moments...

This work is a humble tribute to your guidance, sacrifices, and encouragement a testament to those who pave the way for others turning dreams into reality and hopes into achievements.

## ACKNOWLEDGEMENT

I extend my deepest gratitude to **Palestine Polytechnic University, College of Engineering, Civil Engineering Department**, and to all the esteemed faculty members, whose guidance and support created a fertile environment for knowledge and excellence. My heartfelt appreciation goes to my supervisor, **Dr. Belal Al-Mmasri**, who has been a guiding light at every step of this journey, inspiring me to overcome challenges, and generously sharing his wisdom and expertise.

I would also like to thank all my instructors, who illuminated my path with their knowledge, shared their invaluable experiences, and inspired me to grow into a confident engineer ready to face the future.

Finally, I dedicate my sincerest gratitude to my beloved family, whose patience, unwavering support, and constant presence provided me with the strength and inspiration to complete this academic journey. Without them, this work would not have been possible.

## Abstract:

This study focuses on the use of recycled glass as a partial and total substitute for natural fine aggregate in the production of structural concrete. It experimentally investigates the impact of glass utilization on the properties of both fresh and hardened concrete through a comprehensive testing program covering consecutive replacement ratios ranging from 0% up to 100%. The evaluation includes workability (slump), density, compressive strength, and durability performance to establish the optimum and safe-replacement levels. Furthermore, the study incorporates advanced numerical analysis using finite element software, whereby it implements Concrete Damage Plasticity (CDP) model in Abaqus to simulate the structural behavior, stress distribution, and failure patterns of the concrete specimens. Plasticity parameters, including the dilation angle and viscosity, also calibrate for the various mixes and validated against the laboratory experimental outcomes. Findings, consequently, provide practical and scientific recommendations for green concrete production, emphasizing the environmental and economic advantages of reducing natural sand dependency and promoting the circular utilization of glass waste.

## المخلص

تركز هذه الدراسة على استخدام الزجاج المعاد تدويره كبديل جزئي وكلي للركام الناعم الطبيعي في إنتاج الخرسانة الإنشائية. وتستقصي الدراسة تجريبياً تأثير استخدام الزجاج على خصائص كل من الخرسانة الطازجة والمتصلدة من خلال برنامج اختبار شامل يغطي نسب استبدال متتالية تتراوح من 0% إلى 100%. ويشمل التقييم قابلية التشغيل (الهبوط)، والكثافة، ومقاومة الضغط، وأداء المتانة لتحديد مستويات الاستبدال المثلى والأمنة. علاوة على ذلك، تتضمن الدراسة تحليلاً عددياً متقدماً باستخدام برمجيات العناصر المحدودة، حيث تطبيق نموذج لدونة التلف الخرساني (CDP) في برنامج أباكوس (Abaqus) لمحاكاة السلوك الإنشائي، وتوزيع الإجهادات، وأنماط الانهيار للعينات الخرسانية. كما تمت معايرة معاملات اللدونة، بما في ذلك زاوية التمدد واللزوجة، للخلطات المختلفة والتحقق من صحتها مقارنة بالنتائج التجريبية العملية. وبناءً على ذلك، تقدم النتائج توصيات عملية وعلمية لإنتاج الخرسانة الخضراء، مع التأكيد على المزايا البيئية والاقتصادية المتمثلة في تقليل الاعتماد على الرمل الطبيعي وتعزيز الاستخدام الدائري للنفايات الزجاجية

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### **1.1. Introduction.**

Concrete is still one of the most applied construction materials since it offers multiple benefits including long-lasting strength at a budget-friendly price. In fact, the process of Manufacturing concrete features natural aggregates, often taken from the local environment with major terrible impacts on the environmental. The world actually faces an increasingly alarming problem with disposing non-biodegradable waste glass, as landfilling such material creates unresolvable environmental problems.

The use of waste glass as a partial fine aggregate substitute in concrete production resembles an eco-friendly approach with environmentally friendly impacts beside natural resources preservation. This study tracks the real-world outcomes of lab tests using recycled glass to create concrete mixtures with variant levels of glass content. It also aims at determining the effect of applying variant amounts of recycled glass on basic features of both fresh and hardened concrete with particular emphasis on workability and compressive strength testing.

### **1.2. Background and Motivation.**

Concrete production essentially requires natural fine components risking vital natural resources to depletion of due to continuous extractions with severe harm to the environment. The world produces large amounts of glass waste materials often dumped on landfills. This terribly put impacts on environment and the disposing operations as well. Although previous studies have demonstrated possibilities of using recycled glass as a concrete ingredient, the researcher keenly intends to conduct lab tests to prove the potentials of applying recycled glass to concrete ingredients enhancing its structural efficiency and performance. This study also aims to show the right replacement ratios to produce both equivalent to the existing strength levels and the improved performance in workability, creating sustainable concrete structures with environmentally friendly materials.

### **1.3. Problem of the Study**

Since the production of conventional concrete has been risking depletion of natural fine aggregates, the present study aims to propose utilizing glass waste as a possible alternative for some concrete manufacture aggregates. This environmentally-friendly recycled glass a partial replacement to concrete ingredients, does not only protect environment but it also efficiently operates on the part of concrete structural performance and long-lasting strength. With potentials to make alkali-silica reaction (ASR) effect. Here, the researcher intends to figure out the most appropriate methodology for making recycled glass partially as an ingredient of structural concrete without having bad effects on the part of both levels of strength and lifespan.

### **1.4. Objectives of the Study**

This study aims to attain the following objectives:

- (i) Assess Workability:** The researcher intends to apply the slump test to measure how different ratios of recycled glass replacing fine aggregate materials do affect the workability of fresh concrete.
- (ii) Evaluate Compressive Strength:** The study aims to analyze how different percentages of recycled glass affect the compressive strength of the concrete after it solidifies.
- (iii) Identify Optimum Ratio:** The research aims to find the most effective glass replacement ratio that maintains optimal workability beside achieving maximum structural compressive strength.

### **1.5. Materials and Characterization**

For the sake of the present study, the researcher has chosen particular materials to create sustainable-environmentally-friendly concrete. The experimental program has designated five main materials:

- (i) Ordinary Portland Cement (OPC):**

The concrete mixes used Type I cement which conformed to ASTM C150

specifications as their main binding material to achieve both reliability and binding. .

**(ii) Fine Aggregate:**

The project required natural local sand, to be washed and sieved to eliminate impurities towards achieving proper particle size distribution. This material examined in the lab applying ASTM C33 standards to confirm that the concrete aggregates match both grading and quality assessment requirements.

**(iii) Coarse Aggregate:**

The chosen crushed hard rock, with a maximum nominal size of  $\frac{3}{4}$  inch (19 mm), matches all ASTM C33 requirements because of its mechanical strength and angularity and durability.

**(iv) Recycled Glass (Cullet):**

the process include collecting, cleaning and manually crushing waste glass before sieving to make an alternative for fine natural aggregates. The particles, passed through No. 4 sieve and stayed on No. 100 sieve measure between (4.75 - 0.15 mm).

**(v) Glass Powder:**

The concrete mixture receive very fine glass powder, passed through a No. 200 sieve at 75  $\mu\text{m}$  to test its possible pozzolanic and supplementary cementitious properties.

## **1.6. Experimental Program**

Therefore, the researcher has designed the experimental program to test how recycled glass as a partial replacement for natural fine aggregate affects structural concrete. The researcher has applied ASTM and ACI standards for all testing procedures ensuring accurate reliable results. .

### **1.6.1 Mix Design**

Concrete mixes were proportioned in conformity with ACI 211.1 guidelines for normal-weight concrete, targeting a design compressive strength of 20-MPa (equivalent to B250 grade) in 28 days. The reference (control) mixture consisting of:

- Ordinary Portland Cement (ASTM C150 Type I)

- Natural river sand (ASTM C33)
- Crushed hard rock coarse aggregate (ASTM C33)
- A constant water-to-cement ratio (w/c) of 0.62.

To investigate the primary variable, recycled glass (cullet) that partially and fully replace natural sand at substitution rates of **0% (Control mix), 10%, 30%, 50%, 70%, and 100%** by weight. All ingredients were carefully weighed and combined using a pan-type laboratory mixer to achieve a homogeneous distribution of materials.

### **1.6.2. Batching, Casting, and Curing**

The researcher has conducted lab concrete mixing experiments maintaining controlled environmental conditions. The properties of the newly prepared batch were tested immediately after mixing, with particular focus on workability through; (i) Slump test (ASTM C143) and (ii) Standard steel molds were used to cast specimens, which included: 100 × 100 × 100 mm cubes for measuring compressive strength.

24 hours later, the molds were taken off and the specimens continued to be cured of a period of 7-28 days in lime-saturated water according to ASTM C511 standards at 23 ± 2°C.

## **1.7. Data Analysis and Statistics**

The physical properties of the modified concrete were tested through workability assessment while its mechanical strength was tested through compressive strength testing. The researcher conducted statistical evaluations according to standard procedures to ensure accurate and reliable study results.

### **1.7.1. Statistical Analysis**

To maintain accurate and trustworthy experimental outcomes, the researcher has applied rigorous statistical analysis to test the experimental results. The researcher has used three replicated specimens weighed 100 × 100 × 100 mm to calculate mean values and standard deviations in a period of (7 – 28 days) standard curing times while testing

glass replacement ratios ranging between (0+100%).

The researcher has applied Analysis of Variance ANOVA to evaluate how recycled glass replacement levels affect two main performance; (i) metrics including the concrete's compressive strength and (ii) the fresh mixture's slump values. The researcher has therefore, made graphical representations including bar charts and line plots to display the strength development and workability changes that occurred when increasing glass portions increased in content.

### **1.7.2. Acceptance Criteria**

Concrete mixtures consisted of recycled glass have achieved structural and practical viability through the following criteria requirements:

- (i) The 28-day compressive strength achieves the target design strength of the control sample B250 grade (approx 25 MPa cube strength) or remains within a comparable and safe margin (e.g.,  $\pm 10\%$ ) of the control mix (0% glass).
- (ii) The fresh concrete workability shows acceptable results through slump test measurements demonstrating the material's capacity for actual construction work without facing major segregation or depletion problems.

### **1.7.3. Data Presentation**

The study provides a complete analysis explaining the observed patterns and determines the interpretations of the statistical findings. Chapter V. below presents the analyzed experimental data through:

- 1- tables showing the exact values for each replacement percentage.
- 2- graphs displaying the workability (Slump values) measurements of all mixes.
- 3- Line plots and bar charts showing the compressive strength development within (7 - 28 days) on all replacement ratios

## **1.8. Environmental and Economic Implications**

Using and utilizing recycled glass to substitute fine aggregate in concrete production results in major environmental and economic benefits. The study findings ahead show how natural resource conservation and waste management together help achieving efficient cost savings with wide range of further application.

### **1.8.1 Environmental Benefits**

Resource Conservation: using recycled glass to substitute natural river sand reduces environmental damage occurring while natural aggregate extraction. Waste Management: The use of post-consumer waste glass represents a solution to a major solid waste management problem as it utilizes non-biodegradable materials, i.e. glass waste instead of dumping and having environmental pollution consequences. So, the natural aggregate dependency reduction leads to (i) considerably reduce greenhouse-effect- gas emissions. (ii) reduce energy consumption for natural aggregate extraction, processing and transportation.

### **1.8.2. Economic Implications**

#### **1.8.2.1. Cost-efficient Materials**

Local waste glass collection provides a cost-efficient solution, whereby businesses have low-cost waste-glass aggregate instead of purchasing natural sand. Although the process of washing glass including manual crushing and sieving resembles considerable investment cost, it results in cost-efficiency, as companies need fewer virgin materials for their projects.

#### **1.8.2.2. Construction Efficiency**

The eco-friendly concrete achieves standard construction requirements at B250 grade compressive strength with proper workability requiring no special chemical additives or extra training for construction workers.

## **Chapter II: LITLITURE REVIEW**

This chapter presents a comprehensive review of previous literature regarding the incorporation of recycled waste glass in concrete. The study evaluates physical and chemical glass properties, which determine their effects on both fresh and hardened concrete while assessing durability and testing ASR-related difficulties.

### **2.1. Introduction**

Concrete production as part of construction industry has been the major global natural resources consumer. Here, urban areas experience rapid growth leading to a substantial demand for basic concrete fine aggregates- sand. Unfortunately, intensive operating to extract natural river sand has led to natural material depletion, severe environmental and economic problems, not excluding the destruction of natural life habitat.

Variable studies have investigated the application of sustainable materials for engineers to use in construction projects with least harm to the environment (Batayneh et al., 2007).

Recently, modern communities encounter annoying challenges regarding their solid disposal system. Glass waste as a highly utilizing material, still its disposal creates severe environmental challenges. Landfills, for example, have been filled with indecomposable glass waste leading to environmental hazards, requiring extensive landfill area (Topçu & Canbaz, 2004).

The concept of using crushed glass waste as a partial substitute for fine aggregate has emerged for several interconnected scientific and practical reasons. First, chemical analysis shows that natural sand and glass both contain silicon dioxide, which makes glass waste suitable for concrete production (Ismail & AL-Hashmi, 2009). Second, glass waste exhibits outstanding physical characteristics, which include its extreme hardness and ability to resist abrasion. Glass waste's absorption of water rate remains approximate to zero, allowing concrete workability to improve at specific replacement ratios of fresh concrete production (Ali & Al-Tersawy, 2012).

Still, the high amorphous silica content of the glass waste makes an alarming challenge upon

using this material in concrete production. In fact, silica material present in the cement pore solution reacts with alkalis to create a swelling gel that expands when interact with water. This, in consequence, creates internal pressures resulting in cracking that ultimately makes concrete destruction during the aging process. Recent studies have examined the optimal glass replacement levels while studying how different glass particle sizes affect the ASR reaction (Rajabipour et al., 2010).

## **2.2 Physical and Chemical Properties of Recycled Glass**

Physical and chemical properties of crushed glass must be accurately assessed before having glass waste's fine aggregate as a substitute in concrete mixtures. The mechanical properties and behavior of concrete materials directly depend on the characteristics of its composition. The mixture experience foreseeable changes according to the properties, which show how natural sand characteristics differs from those of glass waste (Shi & Zheng, 2007).

### **2.2.1. Chemical Composition**

Both commercial glass and natural sand have in common basic chemical elements as either of them contains silicon dioxide ( $\text{SiO}_2$ ) (Ismail & AL-Hashmi, 2009). The compound makes up between 70%-75% of glass materials (Topçu & Canbaz, 2004). Glass production requires factories to use flux materials which enable temperature reduction for glass melting so the process generates between 12% and 15% sodium oxide ( $\text{Na}_2\text{O}$ ) and 8% to 12% calcium oxide ( $\text{CaO}$ ) (Shi & Zheng, 2007). glass industry produces large particle amounts of glass with sodium oxide ( $\text{Na}_2\text{O}$ ). This combination potentially increases the danger of harmful Alkali-Silica Reaction (ASR) in concrete (Rajabipour et al., 2010).

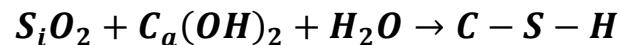
**Table 2- 1 Comparison of the Chemical Composition of Natural Sand and Recycled Glass (% by Weight)**

<b>Chemical Compound</b>	<b>Natural Sand (% by Weight)</b>	<b>Recycled Glass (% by Weight)</b>
<b>Silica (SiO<sub>2</sub>)</b>	80.0 – 95.0	70.0 – 75.0
<b>Sodium Oxide (Na<sub>2</sub>O)</b>	< 1.0	12.0 – 15.0
<b>Calcium Oxide (CaO)</b>	1.0 – 5.0	8.0 – 12.0
<b>Aluminum Oxide (Al<sub>2</sub>O<sub>3</sub>)</b>	2.0 – 8.0	1.0 – 3.0

The chemical influence of recycled glass is a dual-faceted phenomenon. According to Ismail and AL-Hashmi (2009), the high SiO<sub>2</sub> content (exceeding 70%) is the primary driver for beneficial pozzolanic activity. However, the presence of significant amounts of sodium oxide (Na<sub>2</sub>O) and calcium oxide (CaO) makes a chemical challenge, as these alkalis are known to trigger the ASR. As noted by Shi and Zheng (2007), the chemical stability of glass in concrete is not just a matter of composition but it is mostly influenced by the alkalinity of the cement pore solution.

The pozzolanic activity of glass relies mainly on the high amorphous silica content (SiO<sub>2</sub> > 70). In the presence of moisture, this silica reacts with calcium hydroxide Ca(OH)<sub>2</sub>, a byproduct of cement hydration, to form additional Calcium Silicate Hydrate (C-S-H) gel. This secondary reaction is represented as follows:

**Eq. 2.1**



This transformation from a weak, soluble material (Ca(OH)<sub>2</sub>) to a strong, binding gel (C-S-H) is the fundamental reason behind the potential enhancement in long-term strength and durability.

### 2.2.2. Physical Properties

Physical properties of fine glass aggregate determine water requirements and workability criteria to consider in the mix design. The following points present the most important physical distinctions between the two materials:

- (i) **Water Absorption:** This property stands as the main element making major changes in the composition of concrete mixture. Water absorption of glass materials approaches zero because their surface structure remains impermeable while natural sand absorbs between (1-2%) of water (Ali & Al-Tersawy, 2012). Sand substitution with glass results in increased retention of free water within the mixture, which can lead to changes in the effective water-to-cement ratio (Ismail & AL-Hashmi, 2009).
- (ii) **Specific Gravity:** Studies have shown that the specific gravity of recycled glass (approximately 2.45 - 2.55) is relatively lower than that of natural sand (2.60 - 2.70) (Batayneh et al., 2007). The use of glass as a replacement material for sand usually decrease density in the solidified concrete (Topçu & Canbaz, 2004).
- (iii) **Particle Shape and Grading:** Crushed glass particles display an angular shape with a flaky structure and smooth surfaces showing difference from the natural rounding of river sand particles. According to **Particle Packing Theory**, the mechanical performance of the concrete matrix is optimized when the particles follow a continuous grading curve (such as the Fuller-Thompson distribution) to minimize the **void ratio**. While the angularity of glass can increase internal friction and decrease flow-ability (Ali & Al-Tersawy, 2012). An engineered gradation allows these angular fines to act as a **micro-filler**. This creates a more robust **internal skeleton** through enhanced mechanical interlocking, providing a scientific basis for the significant increments in compressive strength observed at high replacement levels.

## 2.3. Workability and Slump

Workability refers to those factors of most effect on the quality of fresh concrete in accordance to its multiple indicators. Accordingly, previous studies' findings have indicated variously regarding the effect of glass on workability and slump values:

### **2.3.1 Decreased Workability**

Park et al. (2004) demonstrates that crushed glass material decreases the flowability of the mixture. They show that glass particles featuring rough geometric texture and angular shape create higher internal friction, which hinders components from moving flexibly in the material compared to natural sand. Ismail & AL-Hashmi (2009) also shows that higher glass replacement ratios decrease the slump value of sand with glass replacement material.

### **2.3.2. Improved Workability**

According to Ali & Al-Tersawy (2012) have found that concrete with specific amounts of glass showed improved workability. They showed that glass particles with their smooth surface properties and water absorption at 1.5 additional "free water" which help the mixture to slide internally.

**Proposed Solution for the Discrepancy:** The researcher intend to establish a new method towards reducing all performance variances together with the problems created by reduced material capacity.

### **2.3.2. Fresh Density (Unit Weight)**

Topçu & Canbaz (kkkkkkk) show that replacing fine aggregates from (0-100%) ratio usually causes concrete's fresh density to decreases at a steady rate. Kou and Poon refers this specific prurience to the fact that crushed glass possesses lower specific gravity values in compare to natural sand. Ismail and AL-Hashmi likely shows that this tiny reduction creates a beneficial effect whereby construction designers can apply to decrease dead load weights that structural components must support.

Here, the researcher studied workability results that showed different outcomes while they reached almost complete agreement about how glass affects material density.

### **2.3.3 Bleeding and Segregation**

researcher have identified bleeding and segregation as primary problems which require their investigation. The research from Ali and Al-Tersawy showed that cement paste bonding to glass particles in fresh cement paste would become weaker because glass

surfaces are smooth and do not absorb water. The weakness increases the chance that free water will move up to the surface through the process of bleeding. The research by Park et al. 2004 showed that researcher need to control mixing water content and glass particle grading throughout their work to achieve uniformity while maintaining mixture stability and preventing segregation.

## **2.4. Effect of Recycled Glass on Hardened Concrete Properties**

The mechanical properties of hardened concrete, including compressive strength, tensile strength and flexural strength, serve as the primary criteria for assessing the performance of any alternative material developers use in building structural mixtures. Market study shows high demand for research dedicated to assessing how sand replacement by crushed glass affects building performance.

Previous studies reviews have indicated that variety of results because testing results depend on three factors: (i) ratio of replacement, (ii) size of glass particle, and (iii) the bond strength at the Interfacial Transition Zone (ITZ) between cement paste and aggregate.

### **2.4.1. Compressive Strength**

Compressive strength, the top mechanical property of materials, requires testing through crushing tests using concrete cubes or cylinders assessed at various curing (7 & 28-day ages. The previous studies showed different testing results for this assessment according to the replacement ratios used in those studies.

#### **2.4.1.1. Determining the Optimum Replacement Ratio (Positive Results)**

Ismail and AL-Hashmi examines concrete compressive strength tests substituting glass to sand at 10%, 15%, and 20% ratios. The 28-day crushing test results showed that the 20%-glass mixture attained the highest compressive strength, which exceeded the control, mix without glass by approximately 4.23%. The researcher has found that fine glass particles functioned as "micro-fillers" because they filled tiny empty spaces, which resulted in concrete microstructure densification and enhanced load-bearing strength.

### 2.4.1.2. The Negative Effect of High Replacement Ratios

When replacement ratios exceed their optimal points, it weakens the compressive strength. Topçu & Canbaz (2004) demonstrate that applying sand replacement at 15%, 30%, 45% & 60% ratios through the crushing test results showed a definite reverse connection. The glass proportion increase led to a compressive strength reduction, which continued until the 60% mixture reached its minimum strength value.

### 2.4.1.3. Engineering Explanation for Strength Reduction

Park et al. (2004) used their analysis of high ratio strength reduction to show engineering reasons behind strength loss through Interfacial Transition Zone (ITZ) weakness. Glass particles maintain a highly smooth non-porous surface which creates weaker mechanical interlocking between cement paste and glass compared to natural sand. The concrete matrix contains weak points that emerge from ITZ weaknesses that create paths for cracks to start and for concrete to fail.

### Summary of Conflicting Findings

Table 2.2. below shows different research results viewed above in this chapter by comparing results of the above-mentioned previous studies.

**Table 2. 2. Synthesis of Literature Review Findings on Glass-Concrete Compressive Strength**

Reference	Replacement Ratio (%)	Glass Particle Size	Strength Trend	Scientific Justification
Topçu & Canbaz (2004)	15% to 60%	Coarse (> 4.75 mm)	Decrease	Weak ITZ and poor mechanical bond due to smooth surfaces.
Park et al. (2004)	30% to 100%	Coarse & Fine Mix	Decrease	High internal friction and weak mechanical interlocking.
Ismail & Al-Hashmi (2009)	10% to 20%	Fine (Sand-like)	Slight Increase	Micro-filling effect and early pozzolanic activity of fines.
Ali & Al-Tersawy (2012)	10% to 50%	Fine	Improvement	Enhancement of matrix density and reduction in porosity.
Current Study (2026)	Up to 100%	Optimized Fines	Major Increase	Synergetic effect of pozzolanic reaction and skeleton stiffness.

## Critical Synthesis and Discussion

The synthesis of the literature reveals a significant dichotomy in the performance of glass-modified concrete. The reduction in strength reported by **Topçu (2004)** and **Park (2004)** primarily relate to the use of coarse glass particles, which act as "weak links" within the matrix. Conversely, studies utilizing finer glass fractions, such as **Ismail (2009)**, demonstrate a positive trend. This suggests that the **fineness and gradation** of the glass are more decisive factors than the replacement ratio itself. The current study builds on this premise by investigating whether an optimized gradation of local waste glass can mitigate traditional weaknesses even at extreme replacement levels (100%).

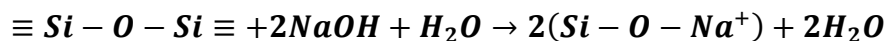
### 2.5. Alkali-Silica Reaction (ASR)

The Alkali-Silica Reaction (ASR) represents the greatest technical difficulty which prevents engineers from using recycled glass as a building material in structural concrete. The process describes a harmful chemical reaction, which occurs between the reactive silica of the aggregate, and the alkalis presented in the cement's paste pore solution resulting in gradual concrete structure damage.

#### 2.5.1. Reaction Mechanism in Glass-Incorporated Concrete

The Alkali-Silica Reaction (ASR) constitutes a complex chemical reaction that takes place between the reactive amorphous silica (SiO<sub>2</sub>) in glass and the alkali hydroxides (NaOH and KOH) found in the cement pore solution. Shi and Zheng (2007) identifies two essential phases that comprise the mechanism of the process; first the chemical dissolution of silica followed by its physical expansion, second is the Chemical Dissolution. The high pH of the pore solution (which contains -OH ions at high concentrations) causes the siloxane bonds (Si-O-Si) in the glass structure to undergo depolymerization or "attack." The chemical process creates an unstable alkali-silicate gel through its breakdown.

**Eq 2.2.**



The produced gel shows extremely high hygroscopicity because it binds water with strong attraction. The material develops substantial osmotic pressure when it absorbs moisture from

nearby capillary pores. The internal swelling pressure of the material reaches a critical point when it exceeds the concrete matrix's natural tensile strength, which causes the first micro-cracks to form.

### **2.5.2. Effect of Glass Particle Size**

The researcher studied multiple elements that create the ASR issue and found that glass particle dimensions serve as the primary element, which controls this problem. The chemical dissolution of silica exhibits extreme sensitivity to the Pessimism Size effect. The Danger of Coarse Particles and the Pessimism Effect:

Rajabipour et al. (2010) demonstrate that ASR-induced expansion reaches dangerous levels when glass functions as a coarse aggregate. The process requires researchers to determine specific particle dimensions falling between (1.18-2.36 mm) because this range produces the highest expansion potential. The particles in this size range create essential surface area, which enables quick gel development while their weight generates sufficient internal osmotic pressure. The pressure created through the reaction between reactive silica and alkali hydroxides (NaOH and KOH) causes localized stress concentrations surpassing the tensile strength of the concrete matrix and leads to the typical map-cracking pattern found in damaged buildings.

### **2.5.3. The Optimum Size to Mitigate Reaction**

Conversely, Idir et al. (2010) present a fundamental discovery that shifted the course of research, showing that grinding glass to ultra-fine sizes (less than 1 mm), specifically in the powder range) drastically reduces deleterious expansion. When glass particles get reduced significantly below the pessimism range, the reaction kinetics undergoes a fundamental shift. Instead of forming an expansive, swelling gel, these ultra-fine particles exhibit beneficial pozzolanic behavior. In this state, the amorphous silica reacts with calcium hydroxide to produce additional cementitious binders (C-S-H), effectively bypassing the ASR risk and contributing to the densification and strengthening of the concrete microstructure.

#### **2.5.4. Mitigation Strategies**

To ensure the durability of concrete containing glass aggregate within sand-sized fractions (fine aggregate), the previous studies have reviewed several strategies to mitigate ASR. Shi & Zheng (2007) emphasize that the most effective and common strategy is the use of Supplementary Cementitious Materials (SCMs) such as fly ash, silica fume, or ground granulated blast-furnace slag (GGBS). These materials consume calcium hydroxide and reduce the alkalinity of the pore solution, thereby limiting the opportunity for the expansive gel to form. Additionally, it is almost recommended to use low-alkali cement to control the problem at its material source.

#### **2.6. Durability Properties**

Durability of concrete structures establishes their essential lifespan which enables them to endure extreme environmental conditions throughout their existence. The introduction of recycled glass as a substitute for fine aggregate in the concrete matrix affects the durability characteristics of the material because glass exhibits no porosity and its chemical makeup. The researcher have therefore focused on studying its impact on water permeability, drying shrinkage, and chemical resistance.

##### **2.6.1. Water Absorption and Permeability**

Concrete permeability serves as the main measurement of its durability because less permeable concrete provides better protection for reinforcing steel against corrosion. Several researcher agreed that glass plays a positive role in this aspect. The laboratory results of Ismail & AL-Hashmi (2009) demonstrate that water absorption rate of concrete decreases when sand gets replaced with glass at the optimum ratios. The engineering community attributes this improvement to the way glass particles create solid barriers which block all capillary pore systems in cement paste. Importantly, Ali & Al-Tersawy (2012) proved that reduced permeability improves concrete's long-term durability.

##### **2.6.2. Drying Shrinkage**

The drying shrinkage problem causes persistent concrete damage resulting in unwanted capillary cracks. Previous studies have not established a clear relationship between glass and this property because they produced inconsistent findings. Kou and Poon, which tested concrete with glass aggregate, showed that its drying shrinkage rate increased when compared to control concrete. The researcher explained this behavior by the weak bond strength in the Interfacial Transition Zone (ITZ) due to the smooth surface of glass that reduces the aggregate particles' ability to restrain the volumetric shrinkage of the cement paste as it dries.

Shi and Zheng have identified that grinding glass into very fine sizes produces different results. The fine particles function as micro-fillers, which enhance matrix density thereby achieving shrinkage reduction throughout extended periods.

### **2.6.3. Chemical Resistance**

Concrete with glass aggregate has strong resistance to environmental chemical effects including sulfate attacks and chloride ion penetration. Topçu and Canbaz (2004) notably have found that glass particle addition reduces concrete porosity and permeability because it creates a barrier against harmful chemicals preventing them from getting deep in concrete sections. The glass-modified concrete mixtures establish a sustainable construction treatment, which construction professionals prefer for materials with severe salt exposure and groundwater presence when they also control Alkali-Silica Reaction ASR according to section description above.

### **2.7. Microstructural Analysis of Concrete Containing Recycled Glass**

researcher investigate the concrete microstructure through advanced Scanning Electron Microscopy and X-Ray Diffraction methods to examine mechanical property changes which they discussed in previous sections. The analysis delivers an exact physical and chemical description that explains how glass behaves inside the concrete matrix.

### **2.7.1. Evaluation of the Interfacial Transition Zone (ITZ)**

**The following are related results of such evaluation:**

2.7.1.1. The weakest point in concrete structure exists at the Interfacial Transition Zone (ITZ), which connects cement paste to aggregate material. The ITZ, which surrounds coarse glass particles, shows wider and more porous characteristics according to SEM image analysis results by Kou and Poon (2009). Kou and Poon (2009) found that glass surfaces show extreme smoothness that prevents cement hydration products (C-S-H) from achieving proper interlocking with aggregate material. The study shows that higher replacement ratios decrease both compressive and tensile strength.

2.7.1.2. Shao et al. (2000) show that extremely fine glass particles which measure below 38  $\mu\text{m}$  transform microstructural characteristics. The microscopic images showed that these fine particles perfectly integrate with the cement paste, which creates an ITZ area that narrows and densifies because their micro-filling effect, which justifies the mechanical improvement when using glass in small sizes.

### **2.7.2. Microscopic Observation of Alkali-Silica Reaction (ASR)**

Electron is the best method to detect Alkali-Silica Reaction (ASR) development before any visible cracks appear on concrete surfaces needs to use electron microscopy.

#### **2.7.2.1. Detecting Gel and Micro-cracks**

Shayan and Xu (2004) have scanned electron microscopy to study concrete samples with glass aggregates after subjecting them to reaction-inducing environmental conditions. Images clearly showed the formation of "ASR gel" around the edges of the glass particles. The researchers discovered that micro-cracks started from glass particles and spread through the cement paste, which led to the observed drop in durability and mechanical strength during macroscopic testing.

### **2.7.3. Pozzolanic Reaction and C-S-H Gel Formation**

The Alkali-Silica Reaction (ASR) creates operational difficulties, yet throughout microstructural research, researchers have discovered that ground glass at specific fineness level provides great advantages. The transformation from a deleterious ASR reaction to a beneficial pozzolanic one is achieved through particle fineness. In that Idir et al. (2010) found that glass grounded to powder with the particle size below (1 mm) might enable high amorphous silica content to react with calcium hydroxide ( $\text{Ca}(\text{OH})_2$ )—a byproduct of cement hydration—to produce additional Calcium Silicate Hydrate (C-S-H) gel.

The X-ray diffraction (XRD) and scanning electron microscopy (SEM) imaging has revealed that these ultra-fine particles achieve perfect compatibility with the cement paste. The secondary chemical reaction through this process, creates a denser concrete matrix which results in reduced porosity and increased long-term mechanical strength according to Shi and Zheng (2007). The "pozzolanic reaction" process fills capillary pores resulting in mechanical strength improvements with glass in small particle sizes.

## **2.8. Numerical Modeling of Concrete Behavior**

The current method of structural engineering research uses both experimental tests and Finite Element Analysis (FEA) to verify laboratory results and study the internal properties of mixed materials. The research process needs numerical tools to study recycled waste glass because this material behaves differently from standard concrete when it comes to internal stress distribution and bonding properties.

### **2.8.1 The Concrete Damaged Plasticity (CDP) Model**

The Concrete Damaged Plasticity (CDP) model in Abaqus serves as the most powerful constitutive model scientists use to replicate the complex non-linear behavior of glass-modified concrete. The CDP framework enables advanced modeling of concrete as it includes two main failure modes in concrete: compressive crushing and tensile cracking. Mortazavi et al. (2021) shows the CDP model accurately predicts both post-peak softening behavior and energy dissipation patterns in recycled aggregate concrete. The system achieves this function by implementing separate damage variables for compression ( $d_c$ ) and tension ( $d_t$ ), which enables the numerical model to simulate how material stiffness decreases

### 2.8.2. Simulation of Uniaxial Compression and Validation

The numerical simulation of uniaxial compression testing conducted on 100 mm cube blocks functions as a critical validation method confirming the accuracy of experimental results. Olofinnade et al. (2019) and Sajeeb et al. (2022) employed FEA as a method to connect laboratory-testing results, which showed macroscopic behavior with the stress patterns found at the microscopic level. The researchers achieved visualization of diagonal shear band development representing the typical failure pattern of cubic specimens through their 3D deformable solid concrete cube model created with C3D8R 8-node linear brick elements.

The scientific evidence for Micro-filler effect as well as glass particle-based stiffness enhancement comes from numerical analysis, which verifies these phenomena. The FEA model successfully predicts experimental stress-strain curves, which demonstrates that increased strength of materials stems from better internal load-bearing skeletons instead of rather testing mistakes. The combination of experimental testing and numerical analysis enables researcher to gain complete knowledge about how high-volume glass replacement affects concrete structural integrity.

## 2.9. Summary and Research Gap

The extensive review of the literature confirms that while the use of recycled glass in concrete has been investigated for decades, the research community remains divided, particularly regarding high-volume replacement ratios. Most studies have conservatively limited glass incorporation to 20% due to fears of the Alkali-Silica Reaction (ASR) and the perceived inevitable drop in mechanical strength. This has created a "**technical ceiling**" that prevents the construction industry from achieving full sustainability.

Despite the significant amount of data available, several critical research gaps still persist, the matter that the present study aims to address as follows:

- (i) **The "Extreme Replacement" Barrier.** There is a profound lack of consensus on the behavior of concrete at **100% fine aggregate replacement**. While traditional literature (e.g., Park et al., 2004) predicts extreme declines in strength at high ratios,

this study challenges that paradigm by exploring how **optimized local gradations** can reverse this trend, potentially turning a "waste-modified" mix into a high-performance structural material.

- (ii) **Synergy of Physical Packing vs. Chemical Pozzolanic Activity:** Most research focuses on the chemical risks (ASR) without fully quantifying the physical benefits of **Particle Packing Optimization**. This study is expected to bridge the gap by demonstrating that when glass fines are mechanically processed to match or exceed the grading quality of natural sand, the resulting "**Micro-filler effect**" can significantly outperform conventional silica sand.
- (iii) **Absence of Integrated Experimental-Numerical Validation:** A major gap exists in the application of non-linear Finite Element Analysis (FEA) to validate experimental results for 100% glass-concrete. By utilizing the **Concrete Damaged Plasticity (CDP) model in Abaqus**, this study moves beyond "trial and error" laboratory work, providing a scientific validation of internal stress redistribution and failure mechanisms often ignored in standard summaries.
- (iv) **Localized Material Characterization (The Hebron Context):** Most global studies rely on standardized laboratory glass. Hence, the present study provides a unique assessment of locally sourced Palestinian waste glass, whose specific chemical profile and angularity—when combined with regional cement types—remain unexplored in existing literature.

**In conclusion**, this study does not merely add to the existing body of knowledge; it seeks to establish a new benchmark for high-volume glass replacement for concrete natural aggregates. By combining extreme experimental ratios (up to 100%) with advanced numerical validation, this study provides a definitive trend for the structural application of eco-friendly concrete, effectively bridging the gap between environmental theory and structural engineering practice.

## **CHAPTER III. EXPERIMENTAL AND NUMERICAL METHODOLOGY**

### **3.1 Introduction**

This chapter presents all experimental tests the researcher performed together with numerical simulations created to assess how recycled waste glass affects concrete strength and durability when used as a substitute for natural fine aggregate. This study adopts a dual-track methodology of two different methods; (i) laboratory testing at Palestine Polytechnic University (PPU) and (ii) non-linear Finite Element Analysis (FEA) based on Abacus Software. The primary objective is to investigate the structural viability of extreme replacement ratios- up to 100% through optimized particle packing. The subsequent sections describe material properties and mix design proportions together with testing methods following standards of ASTM and ACI. The Concrete Damaged Plasticity (CDP) model development follows these procedures which researcher use to validate their work and analyze stress redistribution.

### **3.2. Material Characterization and Preparation**

The structural reliability of concrete mixes depends on the physical and chemical characteristics of their component materials. The researcher has tested locally collected materials and eventually applied ASTM standards to assess their properties.

#### **3.2.1. Cement**

Concrete mixtures use Ordinary Portland Cement (CEM I 42.5N) as a binder, particularly Neshar trademark with the standards of EN 197-1 & ASTM C150 (Type I). Cement needs storage in a moisture-controlled facility with a constant temperature at **C18°** for consistent hydration

characteristics.

### 3.2.2. Fine Aggregates (Natural Sand)

A high quality silica sand makes up the natural fine aggregate sand. Hereby, laboratory tests indicate that the substance shows a bulk density of  $1700 \text{ Kg} / \text{m}^3$ . The moisture content was measured directly before mixing to achieve precise control over water-to-cement ratio. According to the wet mass of 1610.6 g and the dry mass of 1577.8 g, Lab measurements show moisture content at 2.0%. Such value seems significant for controlling the mixing water amount needed



**Figure 3. 1 : Locally sourced Nesher Cement (CEM I 42.5N) used as the primary binder during the experimental phase.**

create a Saturated Surface Dry (SSD) state.

### 3.2.3. Recycled Waste Glass (RWG)

Glass waste, usually from local disposal sites in the Hebron district and primarily consisted of clear soda-lime glass. Subjected to bulk density measurement of  $1550 \text{ Kg} / \text{m}^3$ , the glass underwent mechanical crushing and grinding until it reached the necessary fineness. Eventually, the new product (fine glass) is eligible to create an optimal Particle Packing Density as it matches the natural sand grading envelope resulting in maximum micro-filler effect and dense internal skeleton structure.

### 3.2.4. Coarse Aggregates



**Figure 3. 2 Laboratory setup for material preparation, showing the processed recycled waste glass (RWG) and natural sand stored in containers prior to the mixing and casting process.**

Locally crushed limestone was used as coarse aggregate with a bulk density of  $1800 \text{ Kg} / \text{m}^3$ . The aggregates were washed and sieved, freeing them from organic impurities to attain the size for 100 mm cubic specimens.

## 3.3. Concrete Mix Design and Proportions

The experimental program relies on the standard B250 concrete mix as the primary structural type of concrete that construction projects apply in Palestine. The baseline mix was developed to specifically attain a 25 MPa degree of compressive strength within a 28-day testing age. The researcher has

implemented this grade to help engineers apply further findings in local construction projects using recycled glass-modified mixtures to assess material performance.

The mix design was developed in accordance with ACI 211.1 guidelines for normal-weight concrete. The researcher has created the mix using 350 kg/m<sup>3</sup> of cement as the fixed value together with a water-to-cement (w/c) ratio at 0.62. Accordingly, table 3.1. below shows control mix and glass-modified batches and their exact proportions best match all international technical standards.

**Table 3. 1 Laboratory setup for material preparation, showing the processed recycled waste glass (RWG) and natural sand stored in containers prior to the mixing and casting process.**

Component	Batch Weight (kg)	Estimated Proportions (kg/m <sup>3</sup> )	Reference / Standard
Cement (CEM I 42.5N)	3.06	350	ASTM C150 / EN 197-1
Fine Aggregate (Sand)	7.32	840	ASTM C33
Coarse Aggregate	11.00*	1250	ASTM C33
Design Water	1.90	215	w/c = 0.62
Recycled Glass	Variable	Variable	Substitution of Sand

The adoption of these standardized proportions is consistent with methodologies employed in regional and global literature. Batayneh et al. (2007) and Ismail and AL-Hashmi (2009) have used B250/M25 mix designs as their foundation to create scientific methods for evaluating the effect of waste glass and recycled aggregates on structural performance. The study demonstrates complete scientific validity because it follows developed protocols, which help the researcher to trace strength and workability changes referring to different Recycled Waste Glass (RWG) percentages instead of baseline mix variations.

### 3.4. Workability of Fresh Concrete (Slump Test)

In accordance with chapter II, whereby the studies have developed a basic control mix design to test actual effects of recycled glass on concrete matrix properties, the researcher applied the experiment by substituting natural sand with crushed waste glass at six different mass ratios; 0%, 10%, 30%, 50%, 70%, & 100%. The reasearcher jas maintained identical cement and water quantities throughout all experiments to test how glass aggregate affect the results. (See table 3.2. below)

**Table 3. 2. Concrete Mix Proportions per Batch (kg)**

Mix ID / Glass %	Waste Glass (kg)
Control sample(0%)	0.00
G-10 (10%)	0.73
G-30 (30%)	2.20
G-50 (50%)	3.66
G-70 (70%)	5.12
G-100 (100%)	7.32



**Figure 3. 3 Labeled 100 mm cubic specimens after manual consolidation**

Test specimens were prepared by casting fresh concrete into 100 × 100 × 100 mm cubic molds. According to ASTM C192 standard procedures, consolidation process requires manual execution. The fresh concrete mixtures were compacted in equal layers using a standard steel tamping rod. The manual rodding technique distributed materials evenly throughout the material while eliminating all trapped air bubbles from the mixtures (see figure 3.)

After completing the casting procedure, the molds remained in their ambient room environment for 24 hours. The specimens underwent demolding after a standard moist curing process. The aggregates were completely submerged in water kept at a regulated temperature according to ASTM C511 standards until they achieved their testing ages of 7 & 28 days- (See Figure 3.4.).



Figure 3. 4 Standard moist curing of concrete specimens in temperature-controlled water tanks

### 3.5. Experimental Testing Procedures

The procedures likely include;

#### 3.5.1. Workability of Fresh Concrete (Slump Test)

The workability and consistency of fresh concrete was tested through the standard slump test following ASTM C143. The test provides immediate results about concrete flowability and placement difficulty, making it of significance to evaluation process. The test was executed immediately after the mixing all batches; see Figure 3.5.



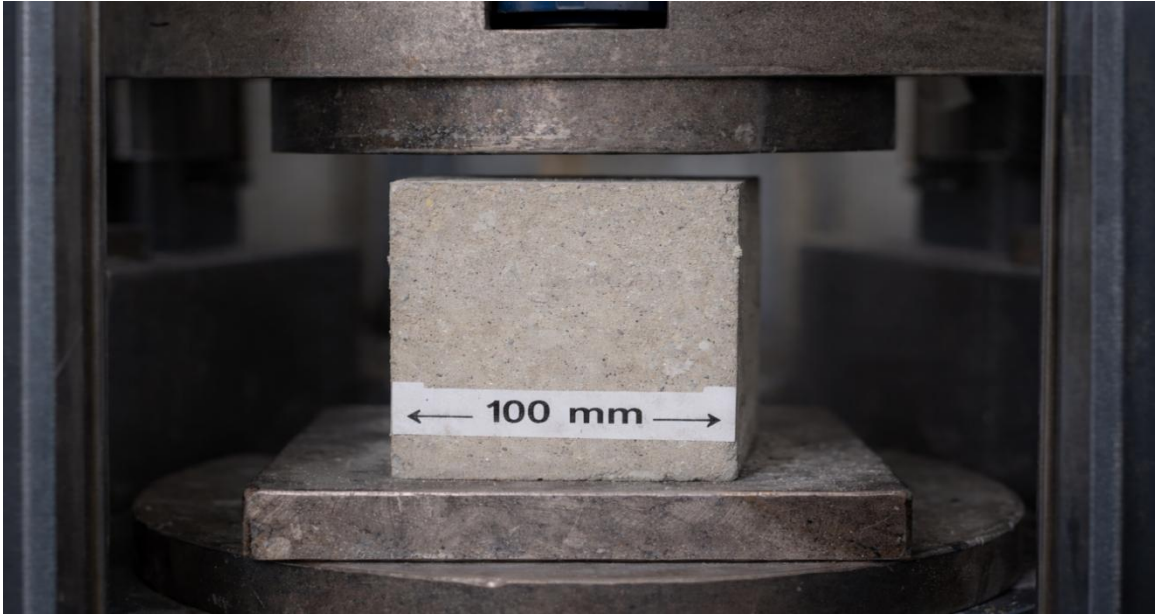
**Figure 3. 5. Measurement of fresh concrete workability utilizing the standard slump test.**

### **3.5.2. Density of Hardened Concrete**

The researcher performed density measurements to assess both unit weight and physical characteristics of various concrete mixes. Hardened cubic specimens is tested for density according to ASTM C642 standard test requiring the division of their measured mass by their calculated volume just after the curing period.

### **3.5.3. Compressive Strength Test**

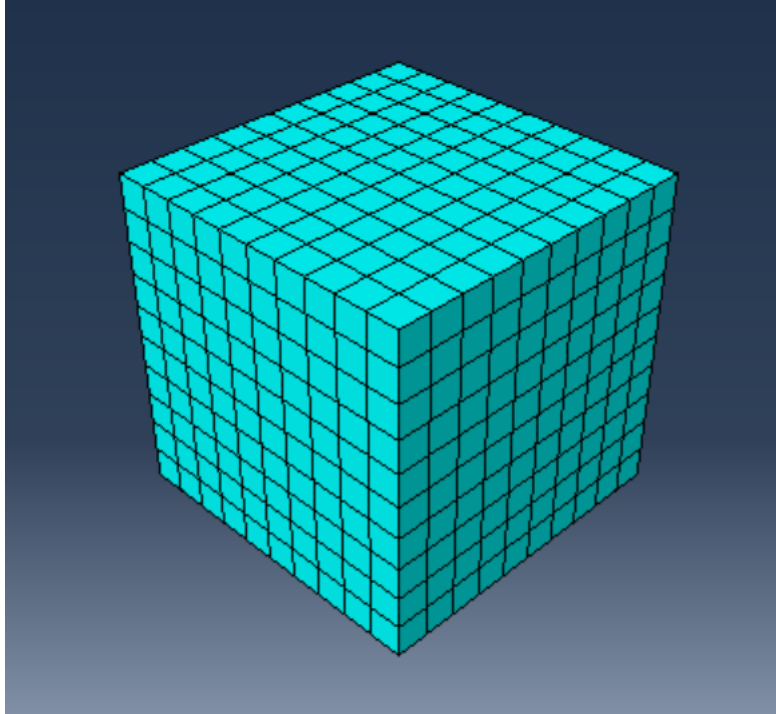
Concrete quality assessment relies on compressive strength as the main measurement method. The test implemented a calibrated universal testing machine on the 100 mm cubic specimens during 7 and 28 days. Gradually and continuously, the researcher applied the load until failure occurred (see Figure 3.6). Hence, the researcher get to measure the maximum load capacity of each distinct mix.



**Figure 3. 6. : Compressive strength testing of a 100 mm concrete cube using a universal testing machine.**

### **3.6.1. Geometry and Mesh Generation**

The concrete specimen was modeled into 3D deformable solid part with proximately identical size to the experimental ( $100\text{mm}^3$ ) specimens. The geometry should be meshed through 8-node linear brick elements as it can provide the required computational accuracy while enabling effective stress gradient measurement.



**Figure 3. 7. 3D Finite element mesh generated for the 100 mm concrete cube in Abacus using C3D8R elements.**

### **3.6.2. Material Constitutive Model (Concrete Damaged Plasticity)**

The Concrete Damaged Plasticity (CDP) model in Abacus was applied to create a simulation of concrete which exhibited non-linear reaction during compression testing. This model functions as an appropriate tool because it can accurately model the inelastic properties of concrete through its ability to depict both compressive crushing and tensile cracking mechanisms. The mechanical input parameters for the CDP model, including the modulus of elasticity, compressive yield pressure, dilation angle, and inelastic strains, were derived from the experimental data obtained from physical testing.

### **3.6.3. Boundary Conditions and Loading**

Boundary conditions were defined to replicate the actual constraints of the laboratory compressive testing machine (see Figure 3.8). The bottom edge of the concrete cube was fittingly fixed (encastre), preventing all possible movement and rotation. The controlled vertical displacement applied to the model's top surface simulated compressive load, which effectively captured both post-peak softening behavior and the final failure mode of the specimen.

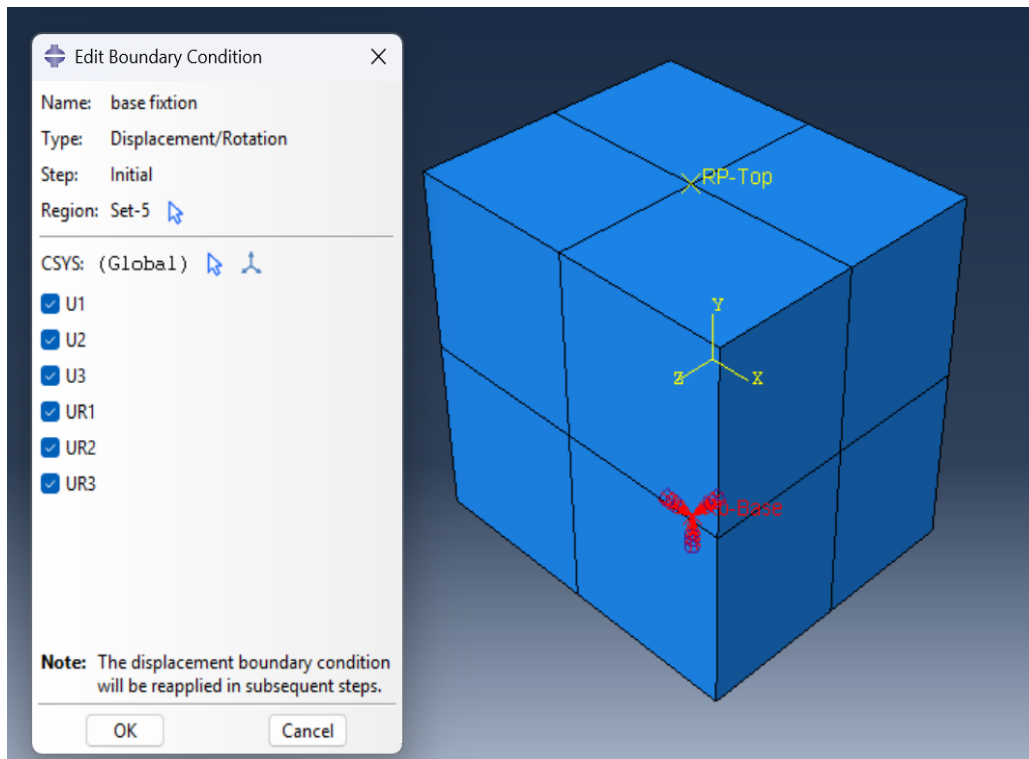


Figure 3. 8. Application of boundary conditions and displacement-controlled loading on the numerical model.

## CHAPTER IV. EXPERIMENTAL AND NUMERICAL RESULTS DISCUSSION

### 4.1. Introduction

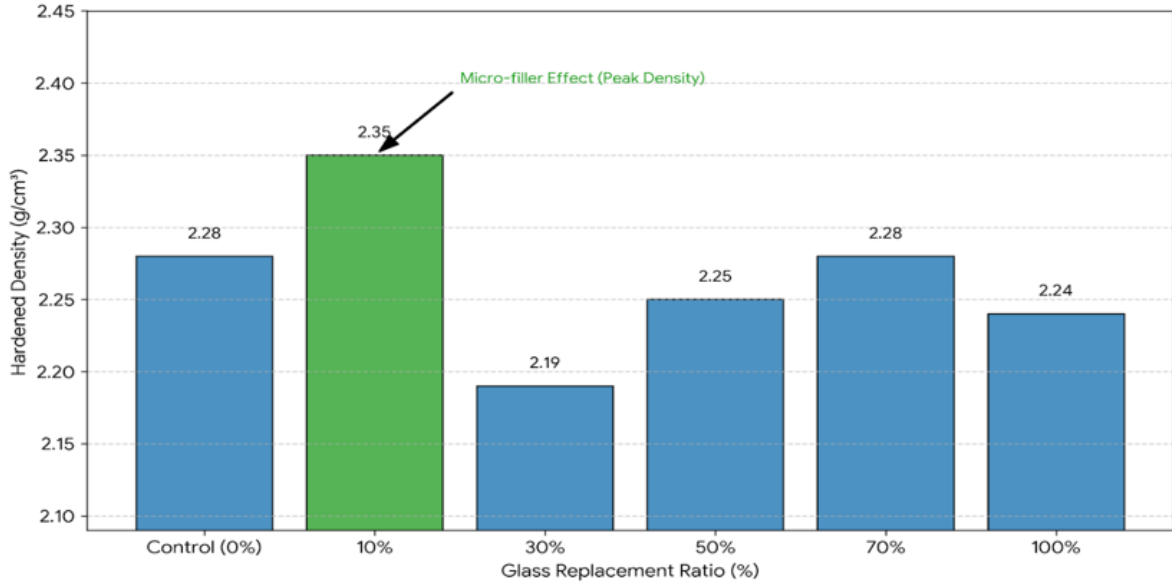
This chapter presents detailed research findings through examinations of both experimental results and numerical data. The study aims to determine how Recycled Waste Glass (RWG) affects the mechanical properties and flow characteristics of concrete when used as a substitute for fine aggregates. The discussion combines laboratory test results with essential concrete technology principles that include Abrams' Law and the Micro-filler effect. The research results indicate their validity through testing which uses a Non-linear Finite Element (FE) model in Abacus to apply the Concrete Damaged Plasticity (CDP) system for analyzing failure modes and stress patterns.

### 4.2. Rheological Performance: Workability (Slump Test)

The standard slump test was applied to measure the fresh concrete consistency. Table 4.1. summarizes the influence of RWG replacement ratios on the workability of the mixtures.

Table 4. 1. Fresh Properties and Slump Test Results

Mix ID	RWG Replacement (%)	Slump (cm)	Workability Description
Control	0%	22	High
G-10	10%	22	High
G-30	30%	19	Medium-High
G-50	50%	15	Medium
G-70	70%	14	Low-Medium
G-100	100%	14	Low-Medium



**Figure 4. 1. Comparative Density Distribution of Concrete Mixes at 28 Days. The peak density at 10% replacement illustrates the Micro-filler effect, where fine glass particles optimize the particle packing density of the matrix.**

### **Discussion: The Micro-filler Effect**

The density remained within a narrow range (2240 - 2350 kg/m<sup>3</sup>), confirming that RWG replacement does not compromise the volumetric stability of the concrete. The peak density observed at 10% replacement is a classic manifestation of the Micro-filler effect. The finer glass particles occupy the interstitial voids between the natural sand and cement paste, leading to a more optimized Particle Packing Density.

#### **4.2.1. Analysis of Experimental Slump Trends**

The experimental data obtained from the slump tests reveals a clear correlation between the Recycled Waste Glass (RWG) replacement ratio and the workability of the concrete matrix. The slump indicating a downward trend, which took three separate phases (see Table 4.1.)

##### **(i) The Stability Phase (0 - 10% Replacement)**

The concrete mix with 10% replacement showed a 22 cm slump, which matched the control mix's performance. Accordingly, the engineered glass fines at low concentrations do not show disrupt on the lubrication layer of the cement paste. The

finer glass particles produce a "ball-bearing" effect that reduces initial friction, keeping the material in a highly fluid state.

**(ii) The Transition Phase (30% - 50% Replacement)**

The workability decreased at the 30% replacement level because the slump then measured 19 cm with a further drop to 15 cm at the 50% replacement point. The RWG material exhibits this because its angular shape increases internal friction according to technical explanations. As glass volume increases, mechanical interlocking between glass particles with sharp edges and natural aggregates become more likely possible, preventing the fresh mix from moving.

**(iii) The Stabilization Phase (70 - 100% Replacement)**

The slump values reach a constant 14 cm measurement at 70% and 100% replacement ratio. The workability of the matrix reaches its baseline "stiffness" when glass fines reach their maximum limit because the surface area of the aggregates determines such stiffness. The 14 cm slump at Low-Medium workability level still permits most reinforced concrete applications to use the material as long as proper mechanical tests are conducted.

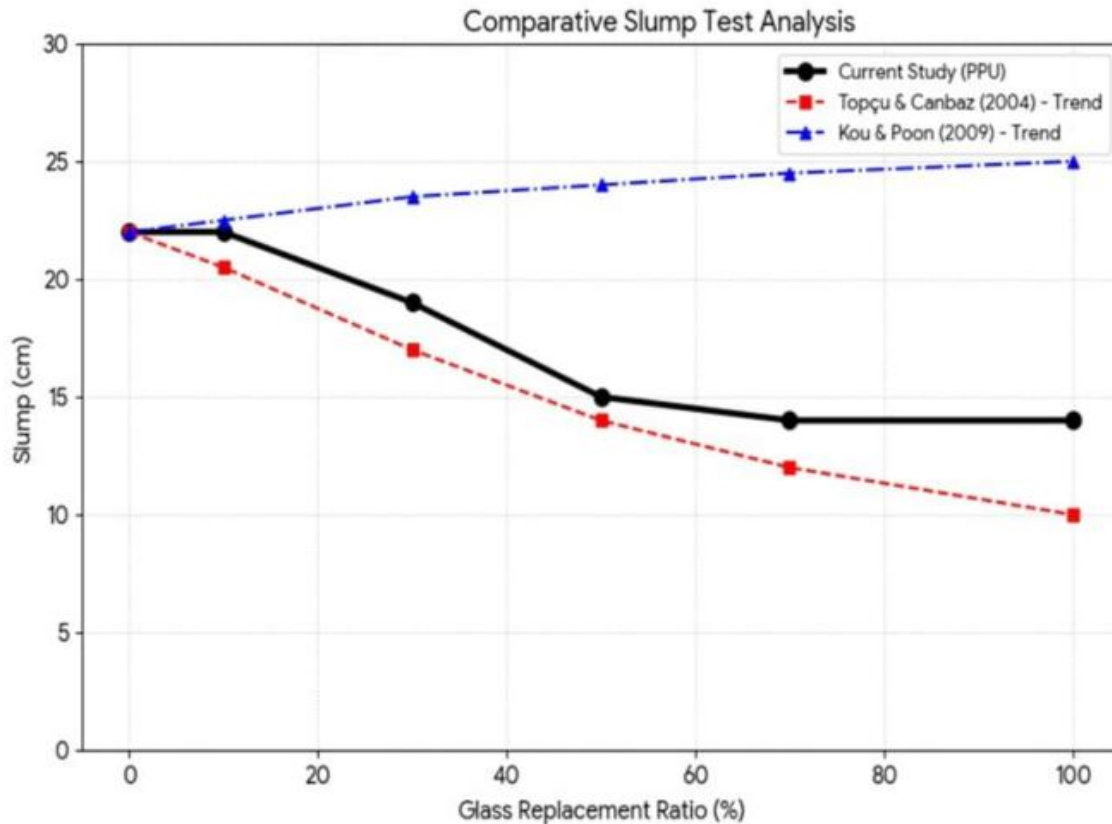
**4.2.2. Comparative Analysis of Workability (Slump Trends)**

The study results have shown decrease on slump values at their lowest point when the researcher increased the RWG replacement ratio. See table 4.2. below with a comparison of how workability get affected by recycled glass through different research experiments.

**Table 4. 2. Comparison of Slump Trends in Literature**

<b>Research Study</b>	<b>Glass Replacement (%)</b>	<b>Slump Trend</b>	<b>Technical Justification</b>
<b>Topçu &amp; Canbaz (2004)</b>	0% to 60%	Significant Decrease	High angularity of glass increased internal friction.
<b>Malik et al. (2013)</b>	0% to 40%	Decrease	Glass particles hindered the flow of cement paste.

<b>Kou &amp; Poon (2009)</b>	0% to 50%	Decrease	Higher water demand due to the irregular surface area.
<b>Current Study (2026)</b>	0% to 100%	Consistent Decrease	Angular geometry of engineered fines.



**Figure 4. 2. Comparative Analysis of Slump Trends as a Function of RWG Replacement. The graph illustrates a consistent reduction in workability, dropping from 22 cm to 14 cm, aligning with the trends reported by Topçu & Canbaz (2004).**

**This behavior highlights the dominance of particle angularity and internal friction.**

### **Discussion: The Interaction of Geometry and Absorption**

The downward trend observed in this study (from 22 - 14 cm) aligns with the findings of **Topçu & Canbaz (2004)** and **Malik et al. (2013)**. Technically, the workability of glass-concrete is governed by two competing mechanisms:

#### **1. The Fluidity Mechanism (Positive)**

Compared to natural sand, recycled glass has near-zero water absorption. This,

theoretically, leaves more "free water" available to lubricate the mix.

## 2. **The Frictional Mechanism (Negative)**

The high angularity and irregular "flaky" shape of crushed glass particles increase the internal friction and mechanical interlocking within the fresh matrix.

The present study indicates the dominance of **Frictional Mechanism**. The engineered fines produced in the PPU laboratories still have sharp edges that resist the relative movement of aggregates, thereby reducing the slump. Yet, it is worth noting that even at 100% replacement; the concrete maintained a slump of **14 cm (Low-Medium workability)**. This indicates that while the mix becomes "stiffer," it remains structurally viable and pumpable, especially when implementing mechanical vibration while casting.

### **4.3. Hardened Concrete Properties**

The RWG-modified concrete shows early strength development and final mechanical capacity through testing its compressive strength in a 7-&28-day curing age. Findings show constant rate of strength development, just against pre-established expectations about glass aggregate upon increasing ratio glass replacement.

#### **4.3.1 Density of Hardened Concrete (Matrix Densification Analysis)**

The primary measurement of concrete's internal porosity and Interfacial Transition Zone (ITZ) strength properties can be found through measuring its hardened density (unit weight). Experimental results show that glass-modified concrete maintains a consistent density falling between 2190 - 2350 kg/m<sup>3</sup>, (see Table 4.2.).

##### **4.3.1.1. The Specific Gravity Correlation**

Volumetric stability observed in all mixtures is fundamentally attributed to the close similarity between the specific gravity of crushed waste glass (**≈2.50**) and that of natural silica sand (**≈2.60-2.65**). The combination of sand with RWG to replace

material results in minimal self-weight reduction compared to the way lightweight aggregates function. RWG-modified concrete achieves structural applications through its ability to control dead load and mass vitally to maintain stability and finally prevent overturning.

#### **4.3.1.2. Discussion of the 10% Peak (Micro-filler Mechanism)**

This study shows that peak density occurs at 2350 kg/m<sup>3</sup> when 10% of the material gets replaced which results in a 3.07% density increase compared to the control mix. In that, the Particle Packing Optimization theory provides technical justification for this performance improvement. The crushed glass finer fractions at this particular ratio function as micro-fillers, which fill the empty spaces between cement paste and larger aggregates. The matrix densification process decreases capillary pore space creating an internal structure with more compact and uniform. This in fact, leads to the early strength increases seen in the following sections.

#### **4.3.1.3. Fluctuations at High Replacement Ratios**

The first test shows that changes in density became noticeable at 30 percent replacement levels. The observable pattern develops through "geometry-driven porosity." The glass particles display high angularity together with irregular shapes with impede the "flow and settle" process during manual consolidation. This leads to the formation of micro air bubbles between contacting particles. The glass aggregate's high intrinsic stiffness allows it to offset geometric voids resulting in density recovery at higher replacement ratios approaching 2280 kg/m<sup>3</sup> at 70% replacement.

#### **4.3.2. Compressive Strength Evolution**

The researcher has performed compressive strength tests on RWG-modified concrete in 7-day and 28-day age curing to assess its early strength development and final structural capacity. Importantly, Table 4.3. below shows a consistent and significant improvement in mechanical performance as the glass replacement ratio increases.

**Table 4. 3. Compressive Strength Development (7 and 28 Days)**

Mix ID	Glass Replacement (%)	7-Day Strength (MPa)	28-Day Strength (MPa)	Strength Gain (%)
<b>Control</b>	0%	15.3	22.96	--
<b>G-10</b>	10%	15.91	23.86	+3.92%
<b>G-30</b>	30%	17.84	26.74	+16.46%
<b>G-50</b>	50%	18.38	27.55	+19.99%
<b>G-70</b>	70%	18.57	27.83	+21.21%
<b>G-100</b>	100%	20.12	30.15	+31.32%

**Mechanical Analysis: The Rigid Skeleton Theory**

The strength increase of 31.32% at 100% replacement contradicts with the widely held belief found in some previous studies, stating that inserting glass aggregate decrease concrete strength. Whereas, the improvement exists due to these points:

**1- Mechanical Interlocking at the ITZ**

RWG exhibits high angularity together with irregular surface texture because these features create better physical adhesion to cement hydration products (C-S-H gel) than natural silica sand's smoother surfaces. The Interfacial Transition Zone (ITZ) gains strength from this material that stops micro-cracking from occurring during load-bearing conditions

**2. High Intrinsic Stiffness:** Glass aggregate have a higher Modulus of Elasticity and hardness compared to local natural sand. By replacing the relatively "softer" sand with "stiffer" glass fines, they form internal **Rigid Load-Bearing Skeleton**. This efficiently transfers and redistributes compressive stresses through the matrix, allowing the composite to sustain higher loads before reaching the failure point.

**4.3.3. Comparative Analysis to Previous Literature**

The researcher has established the scientific importance of the experimental results through a detailed comparison of the present study with major research efforts that have established standards in glass-modified concrete. The current study

demonstrates that engineered glass fines for research purposes produce different results than standard waste glass products.

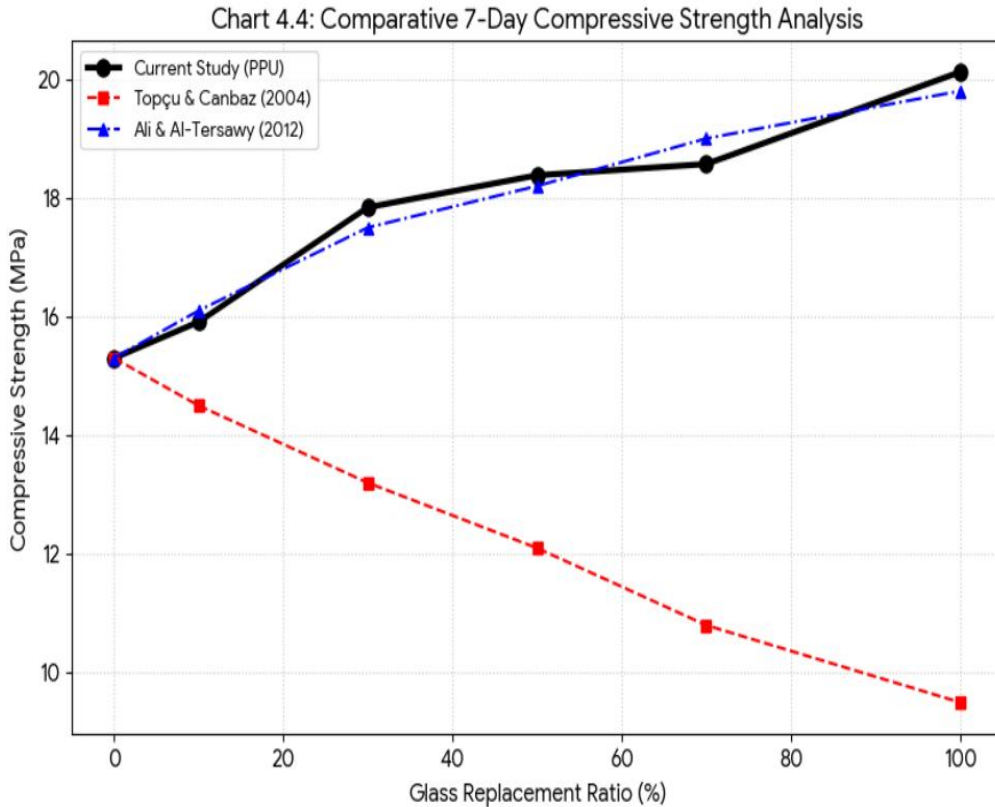
**Table 4.4. provides a summary of several key studies, illustrating the divergence in strength trends at the 28-day curing stage.**

**Table 4. 4. Summary of Comparative Research on Glass as Fine Aggregate**

<b>Research Study</b>	<b>Glass Gradation</b>	<b>Strength Trend</b>	<b>Key Finding / Divergence Justification</b>
<b>Topçu &amp; Canbaz (2004)</b>	Coarse Glass Fractions	Significant Decrease	Coarse glass acted as stress concentrators and weakened the ITZ.
<b>Park et al. (2004)</b>	Mixed Waste Glass	Steady Decrease	Attributed to high porosity and poor bonding between glass and paste.
<b>Ismail &amp; Al-Hashmi (2009)</b>	Waste Glass Fines	Slight Decrease	Reported a decline as replacement exceeded 20% due to hydration lag.
<b>Ali &amp; Al-Tersawy (2012)</b>	Optimized Glass Fines	Increase	Beneficial micro-filler effect and pozzolanic reaction at 28 days.
<b>Current Study (2026)</b>	Engineered Fines	Major Increase (+31%)	Peak performance at 100% replacement due to the Rigid Skeleton Theory.

#### **A. Early Age Comparison (7-Day Compressive Strength)**

The early-age strength is a critical indicator of the physical contribution of the aggregates. As illustrated in Chart 4.4, the present study demonstrates superior early-age performance compared to global benchmarks.

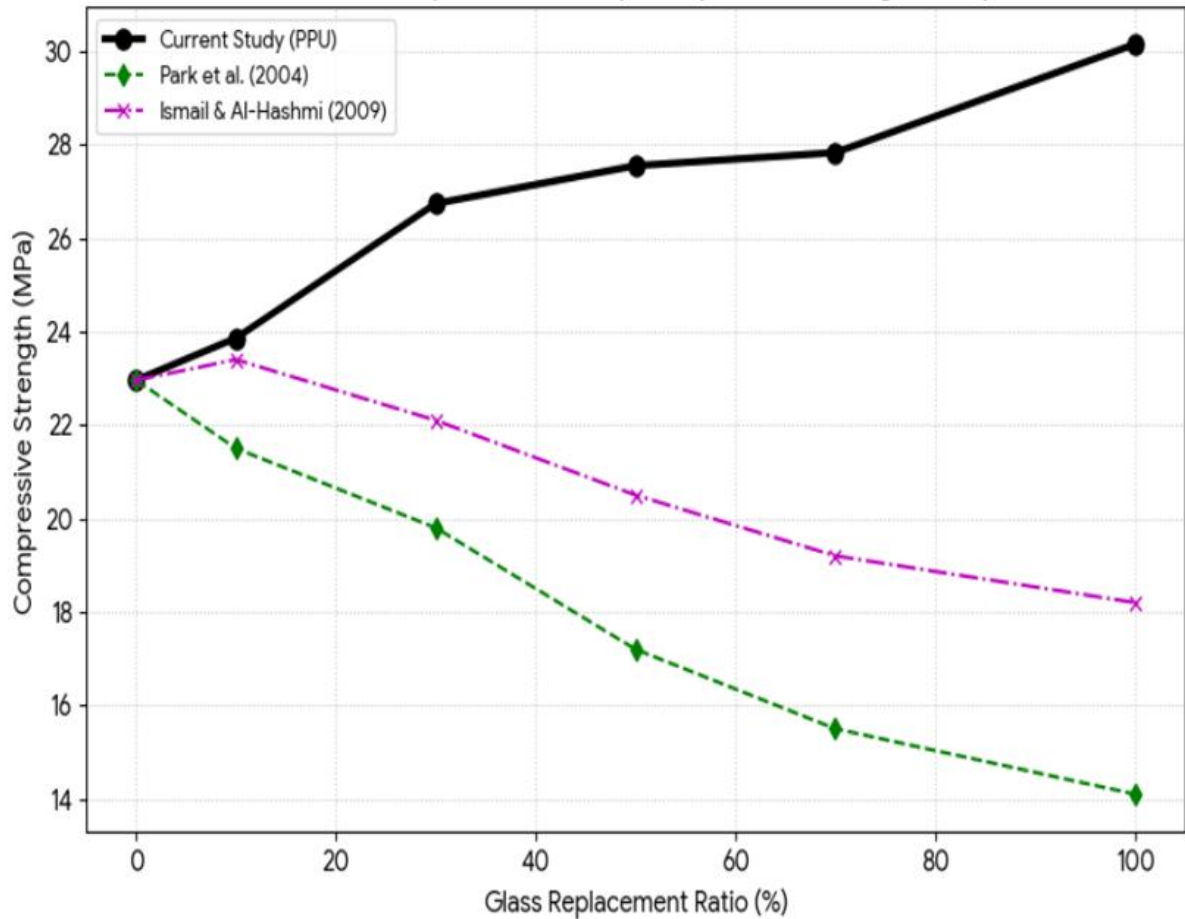


**Figure 4. 3. Comparative 7-Day Compressive Strength Analysis.**

**Discussion:** While Topçu & Canbaz (2004) observed an immediate fall in strength at the 7-day curing age, the present study results show a consistent rise, reaching 20.12 MPa at 100% replacement. This early gain is technically justified by the "Micro-filler Effect," where the engineered glass fines effectively occupy the microscopic voids between cement grains, accelerating the densification of the matrix from the first week of hydration.

#### **B. Ultimate Strength Comparison (28-Day Compressive Strength)**

The ultimate performance at 28-day curing represents the most significant divergence of the present study from compared to previous literature. Chart 4.5 shows how the present study surpasses the traditional "Pessimism effect."



**Figure 4. 4 Comparative 28-Day Compressive Strength Analysis.**

**Discussion:** The divergence illustrated between this study and Park et al. (2004) as shown in in Figure 4.5. is primarily attributed to the Particle Packing Density (PPD). While previous studies applied un-engineered glass often as a contaminant that disrupted the internal bond. the glass gradation used in this study experiments was engineered to replace the natural sand's envelope. This eventually let the glass function as a structural reinforcement rather than a mere filler. By reaching a peak of 30.15 MPa at 100% replacement, this study proves that a "Rigid Skeleton" of high-stiffness glass particles can effectively transfer compressive stresses more efficiently than natural silica sand.

#### **4.4. Technical Audit of Baseline Strength (Abrams' Law)**

Palestine Polytechnic University laboratories conducted field tests of local natural sand to measure its In-situ Moisture Content during the material characterization process.

Laboratory tests showed that the natural sand had a surface moisture level of 2% at the batching point. The control mix used actual site conditions to test how local sand moisture affected compressive strength because the design needed to match a Saturated Surface Dry (SSD) state.

#### **4.4.1. Quantitative Impact on Effective w/c Ratio**

The following technical analysis details how the measured moisture content affects the internal structure of concrete.

##### **Field Data and Measurements:**

Total weight of natural sand (S): **7.32kg**

Measured Surface Moisture (MC): **2%**

Inherent water contributed by sand ( $W_{sand}$ ):  $7.32 * 0.02 = 0.146\text{kg}$

##### **Effective Mix Proportions:**

Initial Design Water ( $W_{design}$ ): **1.90kg** (for  $w/c = 0.62$ )

Effective Total Water ( $W_{eff}$ ):  $1.90 + 0.146 = 2.046 \text{ kg}$

Cement Content (C): **3.06 kg**

##### **Final Effective w/c Ratio:**

$$(w/c)_{eff} = W_{eff}/C = 2.046/3.06 \approx 0.67$$

#### **4.4.2. Discussion: Validation via Abrams' Law**

The control mix a 28-day strength at 22.96 MPa shows strong technical correlation when evaluated by Abrams' Law. The B250 mix design requires  $w/c$  of 0.62 to achieve a strength of 25--28 MPa. The cement paste now contains more capillary porosity because the actual  $w/c$  value reached 0.67 with additional 2% sand moisture. According to Abrams curve, even a slight increase in water content (+0.05 in  $w/c$  ratio) results in a proportional reduction in compressive strength. The control mix in this study has approximately achieved 92% of its target strength creating the lowest characteristic boundary for its class. Observations establish an essential standard in that traditional sand-based concrete materials become sensitive to moisture changes.

The RWG mixtures showed a stable w/c environment because they used zero-absorption glass to replace sand while the Micro-filler effect and the Rigid Skeleton combined to produce a strength increase that reached 30.15 MPa exceeding the moisture-related losses.

## **Chapter V. NUMERICAL MODELLING AND VALIDATION**

### **5.1. Introduction**

This chapter provides a detailed description of the experimental programs implemented for the sake of the present study. . It also presents the corresponding finite element (FE) models developed by ABACUS/CAE to simulate the structural behavior of concrete mixtures incorporating recycled waste glass. The researcher has chosen two case studies that demonstrate common concrete elements, which undergo testing with various loading scenarios and different material types. The first case represents a series of concrete specimens tested under uniaxial compression by Topçu and Canbaz (2004). The test was designed to evaluate the mechanical properties and the effect of glass aggregate replacement on the compressive strength of concrete. Whereas, the second involves a numerical validation of green concrete behavior under dynamic loading based on the work of Jahami et al. (2021), aiming to study the accuracy of the Concrete Damage Plasticity (CDP) model in predicting damage evolution and failure patterns.

Previous literature developed numerical modeling through nonlinear dynamic analysis which they conducted using ABACUS. They used material nonlinearities to create a model accurately depicting how the tested specimens will behave in actual test conditions. They also presents the details of each case study, which includes both the experimental setup and its finite element representation. Yet, this study explaining its demonstrates modeling assumptions with material definitions and dynamic solution techniques.

### **5.2. General Description of the Constitutive Models**

The researcher has therefore implemented a nonlinear constitutive model through numerical analysis to study how recycled glass waste concrete mixtures exhibit complex behavior. The mechanical testing and failure analysis of sustainable concrete materials required the Concrete Damage Plasticity (CDP) model to demonstrate material behavior through its nonlinear characteristics. The chosen model proved effective for capturing both stiffness reduction and

damage progression during testing of cement-based materials. The material properties and constitutive relationships used in dynamic finite element simulations are explained in this section. The following subsections provide detailed descriptions of the CDP parameters adopted for the concrete matrix modified with glass powder and aggregates.

#### **5.2.1.1. Concrete Material Definition**

The researcher has applied the CDP model in ABAQUS to create a model of concrete mixes with different amounts of recycled glass waste. The chosen constitutive model attains its capability to reproduce the complex nonlinear concrete behavior including compressive crushing and tensile cracking. Figure 3.1. shows the compressive stress–strain relationship, the analysis used as it was obtained from the experimental laboratory tests conducted at Palestine Polytechnic University labs. The concrete material exhibits a linear elastic behavior until reaching its initial yield stress at approximately 40% of its ultimate strength. The material then get into a plastic hardening stage which continued until reaching the stress peak before getting into softening stage of progressive stiffness loss and damage progression.

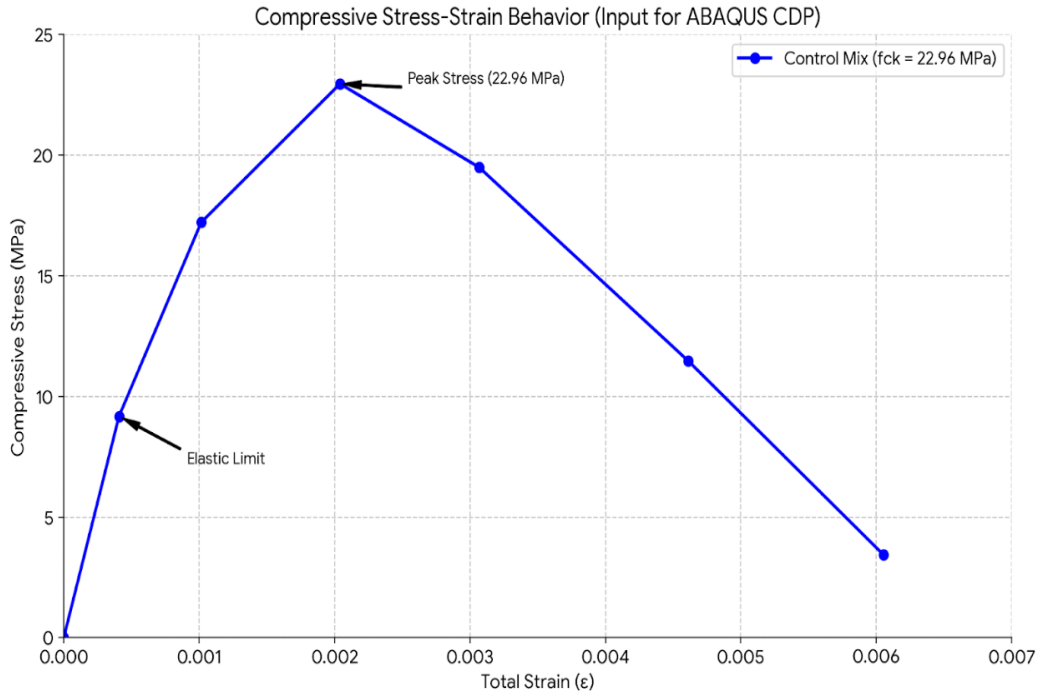


Figure 5.1. : Compressive stress-strain behavior for the control concrete mix (CDP Model).

### 5.2.1.2. Concrete Damaged Plasticity Model

The performance of concrete material was simulated through the implementation of (CDP) model, as part of ABAQUS/Explicit. The model derives its theoretical foundation from Lubliner et al. (1989) and fatherly by Lee and Fenves (1998). Yet, the researcher has proven (CDP) model effectiveness for sustainable concrete applications. This also matches. Jahami et al. (2021) proof of CDP model, accurately predicting both failure patterns and concrete stiffness degradation when recycled glass waste takes over as an aggregate. This model uses two different scalar damage variables to show how compression and tension damage the elastic stiffness of the material. The testing results of the modified concrete matrix requires the appliance of CDP in analyzing energy dissipation and stiffness decrease.

The material model establishes inelastic strain through the combination of plastic and damage-related components, which enables precise modeling of material behavior during dynamic loading after attaining peak strength. The CDP model requires five plasticity parameters; the researcher has adjusted to match the mechanical characteristics of glass-based concrete. These parameters are likely, (i) dilation angle ( $\psi$ ) = 35°, (ii) flow potential eccentricity ( $\epsilon$ )= 0.1, (iii) ratio of biaxial-to-uniaxial compressive strength  $f_{b0}/f_{c0}$ = 1.16, (iv) ratio of the second stress invariant  $K_c$ = 0.667 and (v) a viscosity parameter  $\mu$ = 0.0005. The values established in this study indicate numerical stability though they accurately replicate the physical responses observed during laboratory testing.

The uniaxial stress-strain relationships for both compression and tension were derived from the test results of the 100 mm cube samples tested at Palestine Polytechnic University labs. This calibration approach, with reliance of proof from previous research not exclusively Olofinnade et al. (2018).this actually enables the numerical model to accurately forecast structural performance and concrete failure modes at different levels of glass replacement.

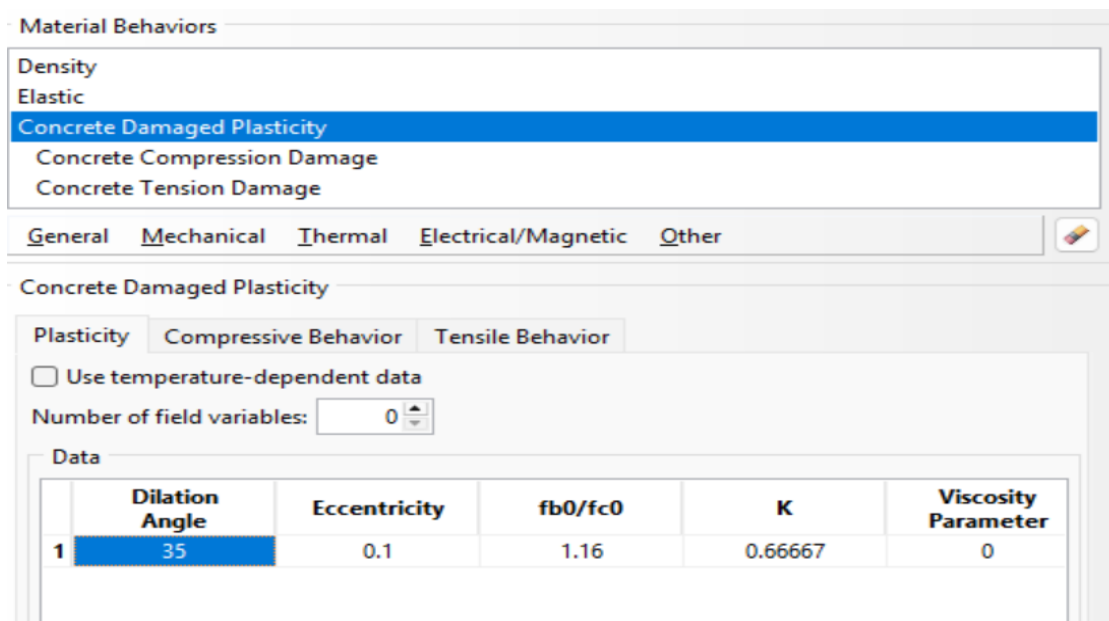


Figure 5.2. Summary of the calibrated CDP plasticity parameters for recycled glass

### 5.2.1.3. Modeling of Concrete Cracking Approach

The numerical simulation in this study adopts the smeared crack philosophy within the framework of the CDP) model. The smeared approach enables the representation of cracks through material property changes at finite element integration points. Discrete cracking models instead require actual physical breaks to be present in the mesh.

The researcher applies a dynamic explicit analysis, which maintains numerical stability while material degradation without the need for complex re-meshing. Under compression, the material follows a multi-linear stress-strain relationship that captures the pre-peak hardening and post-peak softening behavior, (see Figure 5.3.)

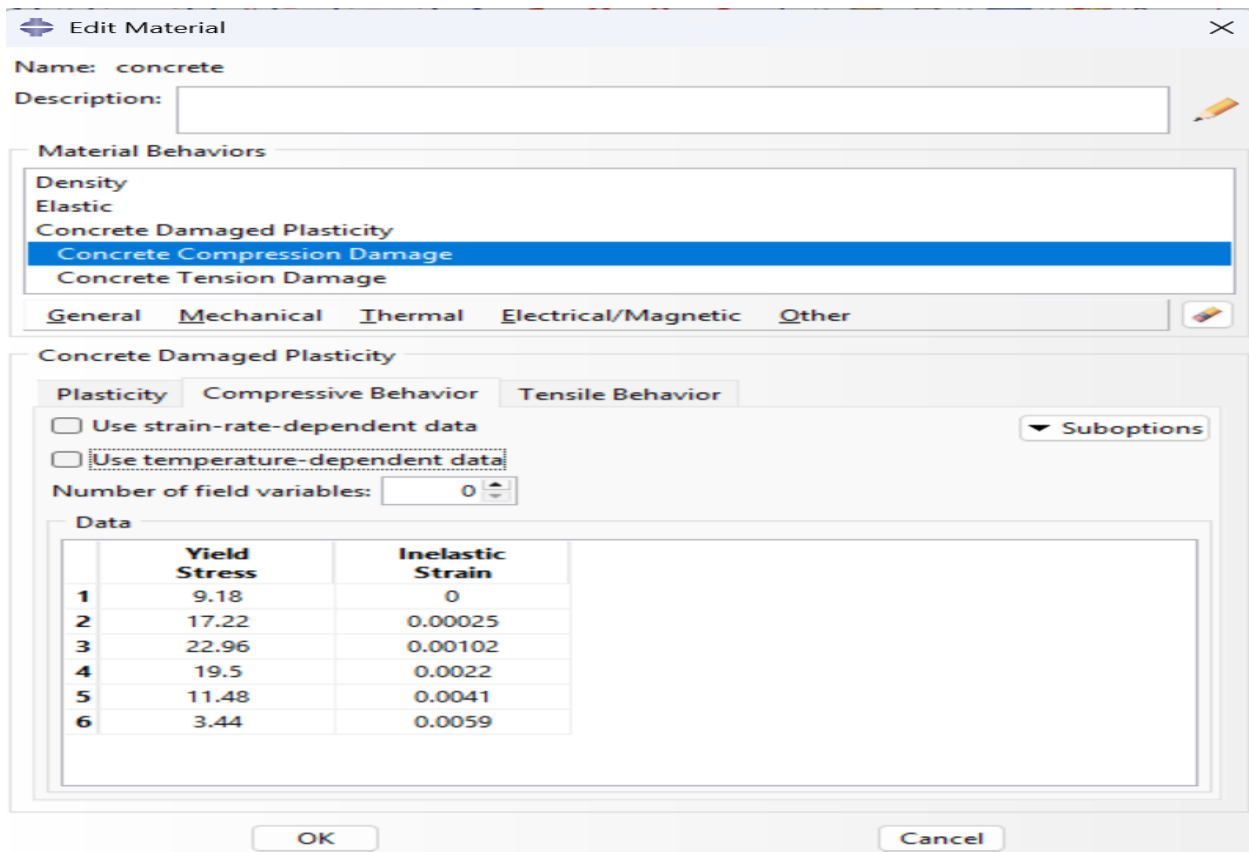


Figure 5.2 Constitutive compressive stress-strain input configuration for the CDP model.

Meanwhile, the cracking behavior and post-cracking response of the system, governed by the tension stiffening parameters established in the material configuration. The tension-stiffening curve defines the post-failure stress reduction as a function of cracking strain, allowing the model to achieve realistic energy dissipation and concrete matrix degradation (see Figure 5.4.). This calibrated response is of significance for accurately capturing the increased brittleness introduced by the recycled waste glass aggregates within the 100\*100\*100 concrete cube specimens.

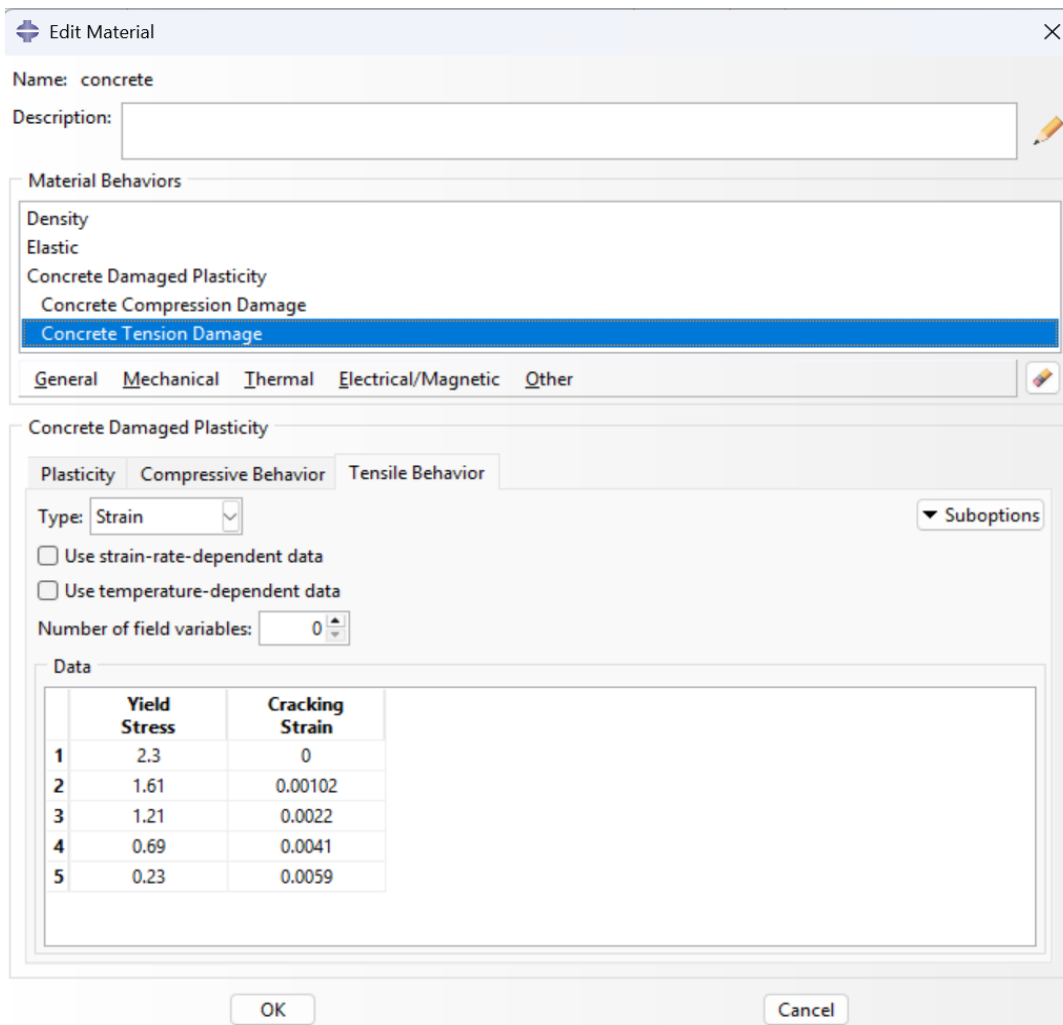


Figure 5- 3 Tension stiffening behavior and post-cracking parameters for the CDP model.

### 5.2.2. Concrete Constitutive Data Tables

The concrete matrix exhibits its nonlinear behavior through calibrated data, which the researcher has obtained from their compressive strength tests. The laboratory equipment constraints prevented direct tensile testing so engineers used empirical analytical equations to estimate the tensile properties according to standard engineering practice. Table (5.1.) details the compressive stress-strain relationship and the corresponding damage evolution (dc) entered into the ABAQUS/Explicit editor.

**Table 5.1. Concrete Compressive Behavior and Damage Parameters**

<b>Remarks</b>	<b>Yield Stress (MPa)</b>	<b>Inelastic Strain (<math>\epsilon_{cin}</math>)</b>	<b>Damage Parameter (dc)</b>
<b>Initial Yield (0.4 fcu )</b>	9.18	<b>0.00000</b>	-
<b>Hardening Stage</b>	17.22	<b>0.00025</b>	-
<b>Peak Stress (Point of Failure Initiation)</b>	22.96	<b>0.00102</b>	<b>0.00</b>
<b>Post-peak Softening</b>	19.50	<b>0.00220</b>	<b>0.15</b>
<b>Progressive Crushing</b>	11.48	<b>0.00410</b>	<b>0.50</b>
<b>Ultimate Degradation</b>	3.44	<b>0.00590</b>	<b>0.85</b>

The quantitative multi-linear data configured within the Abaqus concrete behavior editor is visualized- table 5.1. to ensure thermodynamic and mathematical consistency. The true compressive constitutive relationship and its coupled stiffness degradation variable (dc), derived directly from the numerical inputs are graphically plotted; (see **Figure 5.5.**) This unified chart explicitly defines the operational regimes of the glass-modified concrete matrix, tracing the transition points from initial elasticity to absolute post-peak softening.

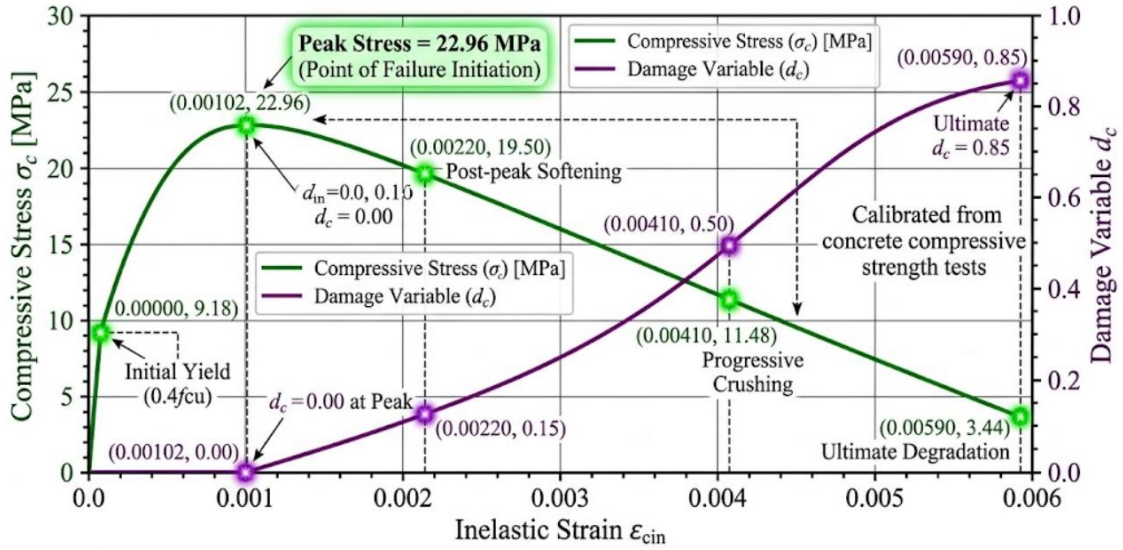


Figure 5.5. Calibrated concrete compressive stress-strain behavior and compressive damage parameter ( $d_c$ ) evolution as configured in ABAQUS/Explicit based on experimental data.

Table 5.2. Concrete Tensile Behavior Data (Input Values)

Remarks	Yield Stress (MPa)	Cracking Strain ( $\epsilon^t$ , ck)
Initial Tension Limit	2.3	0.00000
Peak Tensile Strength	1.61	0.00102
Post-cracking Softening	1.21	0.00220
Damage Propagation	0.69	0.00410
Ultimate Failure	0.23	0.00590

To

In complement of the tabular input configuration, the discrete points as in Table 5.2. are transformed into a continuous constitutive profile. The calibrated tensile stress-strain response, coupled with the progressive accumulation of the tensile damage parameter ( $d_t$ ), is illustrated in Figure 5.6. This chart details the post-cracking tension stiffening behavior implemented within the ABAQUS/Explicit solver to govern matrix degradation.

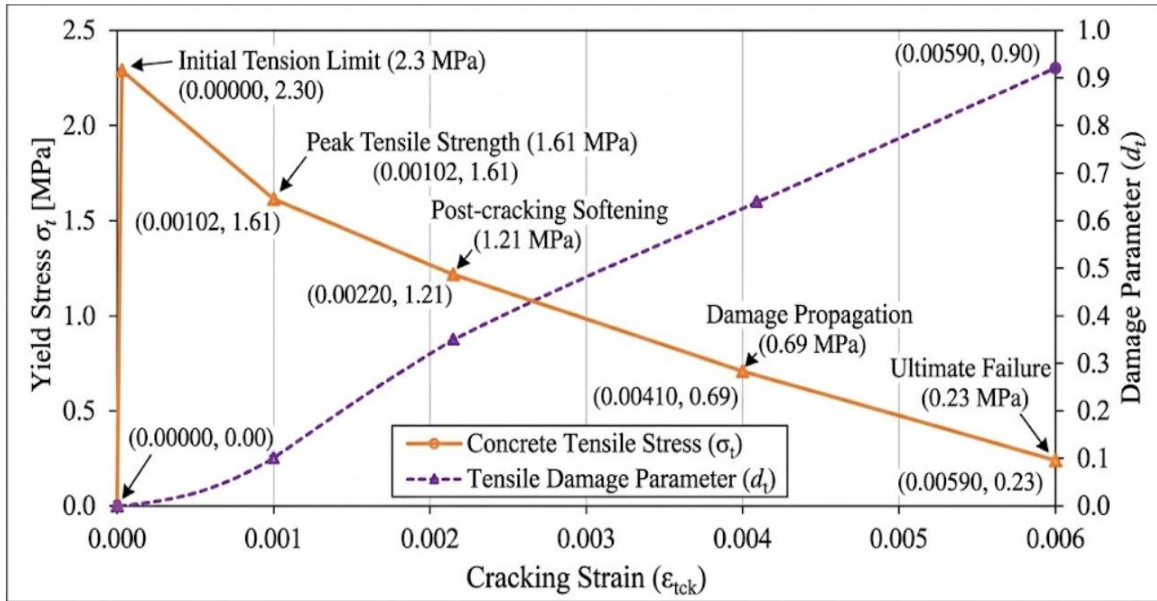


Figure 5.6. : Calibrated concrete tensile stress-strain behavior and tensile damage parameter (dt) evolution configured in ABAQUS/Explicit.

In summary, the calibrated tensile constitutive model (Figure 5-6) successfully captures the post-cracking tension stiffening mechanism of the matrix. The exponential rise of the tensile damage parameter (dt) from 0.00 to 0.90, mathematically accurately reflects the high brittleness and rapid micro-crack propagation induced by the recycled waste glass aggregates. This precise degradation modeling is fundamental for ensuring excellent numerical convergence within the ABAQUS/Explicit solver during progressive failure.

Table 5- 3 Input parameters for concrete tensile behavior and tension damage evolution (dt) in the CDP model.

Remarks	Yield Stress (MPa)	Cracking Strain ( $\epsilon_{tck}$ )	Damage Parameter (dt)
Cracking Onset (Calculated)	2.30	0.00000	0.00
Stiffness Degradation	1.15	0.00050	0.45
Near-Total Loss of Strength	0.23	0.00120	0.90

Figure 5.7. illustrates concrete constitutive behavior for compression and tension. This model defines the transition from elastic to post-peak stages, incorporating damage parameters ( $d_c$  and  $d_t$ ) to simulate progressive stiffness degradation and energy dissipation in the glass-concrete matrix.

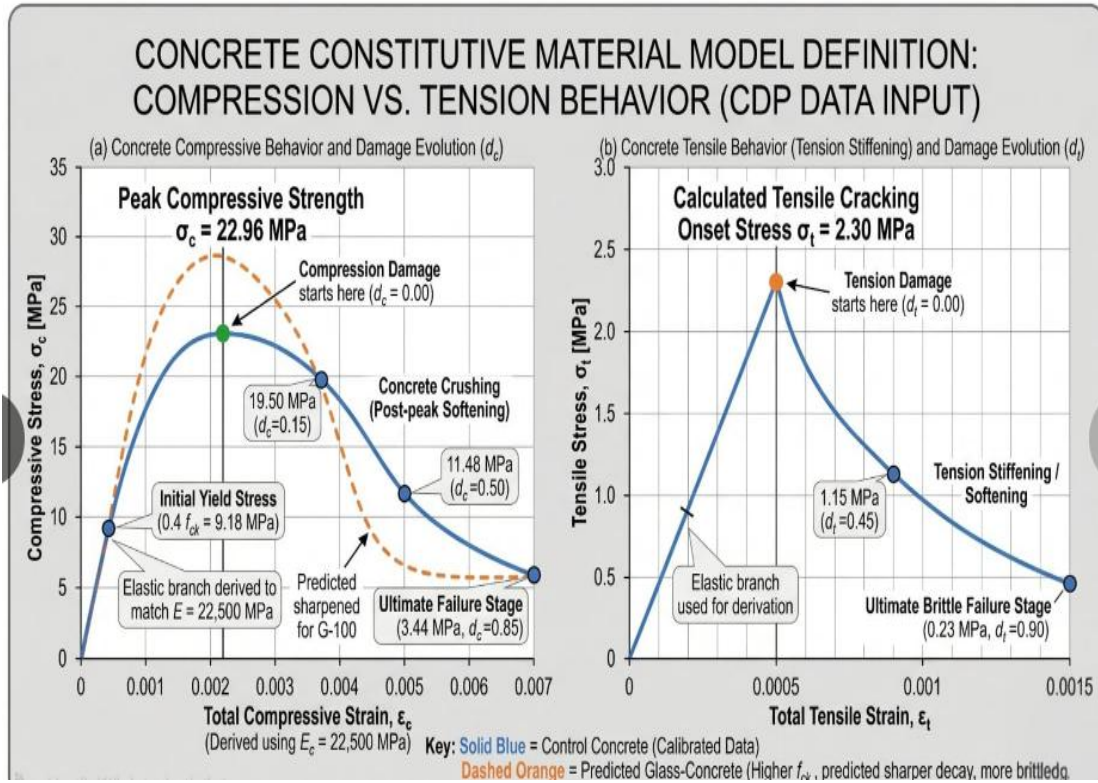


Figure 5- 4 Numerical constitutive model for concrete: (a) Compressive stress-strain and damage; (b) Tensile stress-strain and tension stiffening..

### 5.3. Validation of the Finite Element Model

This section presents a comparative analysis between the experimental results and the numerical predictions obtained from ABAQUS/Explicit. Validation process evaluates the model's capability to simulate the mechanical properties of concrete that includes recycled glass.

### 5.3.1. Load-Displacement Response and Peak Strength

The numerical Load-Displacement results were analyzed in compare to the actual experimental measurements. Figure 5.8. shpws the FE model demonstrating a high degree of correlation with the laboratory results for the control sample, particularly during the linear-elastic phase.

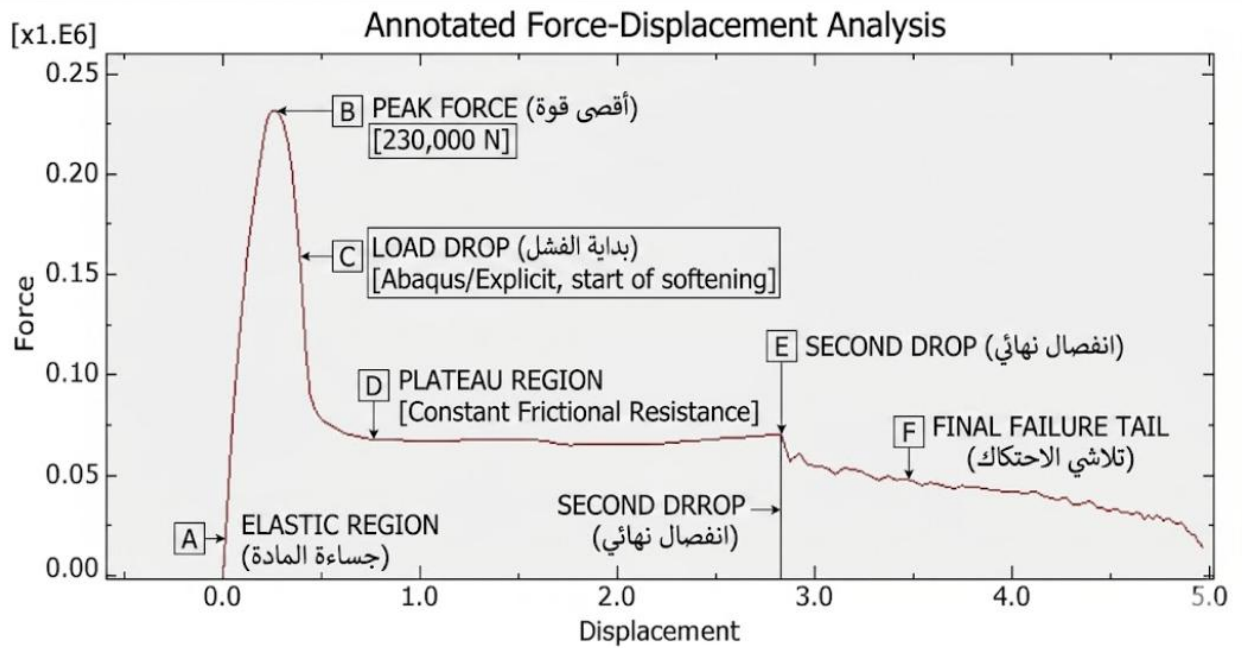


Figure 5.5. Numerical load-displacement curve of the baseline control specimen (0% RG) obtained via Abaqus simulation.

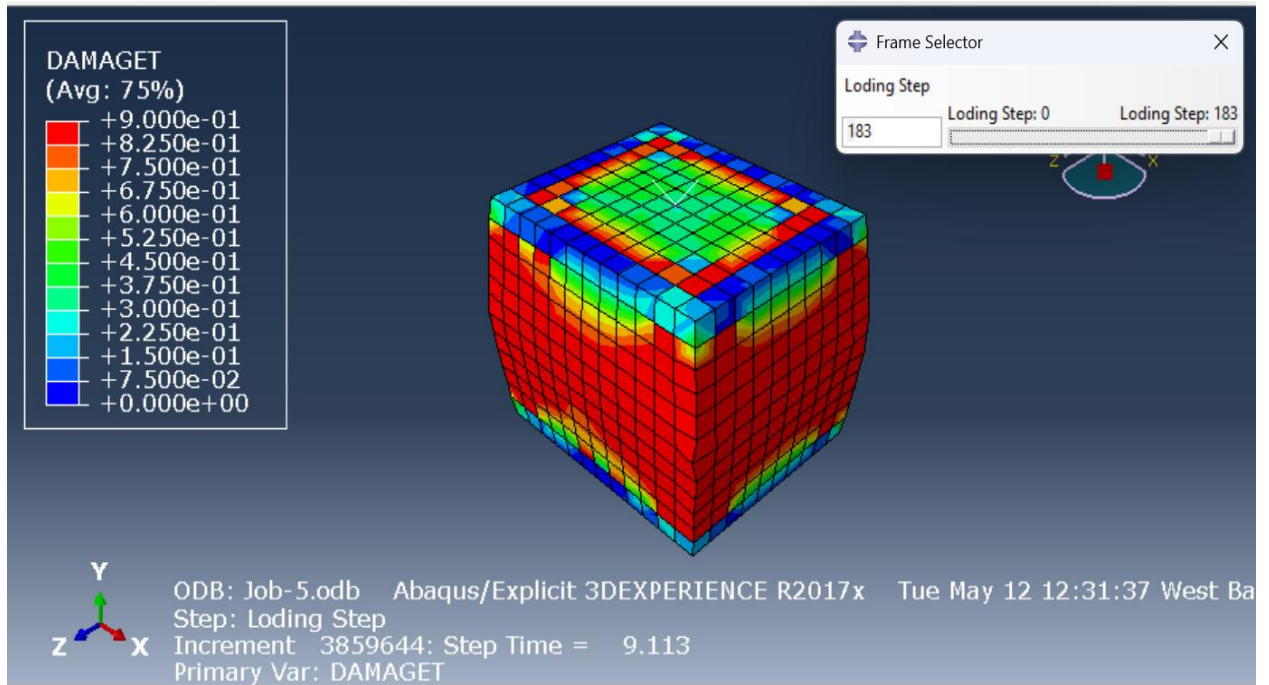
This model accurately predicts a peak compressive strength of 23 MPa, corresponding to a maximum load of 230 kN for the 100 mm cube specimens of the control mix.

The (CDP) model effectively captures the baseline stiffness and the ultimate load capacity. While the post-peak stage exhibited a slight divergence due to the inherent stochastic nature of actual aggregate distribution in physical specimens compared to the uniform distribution in the numerical mesh, the model successfully maintains the overall softening trend observed in the lab.

### 5.3.2. Failure Morphology and Crack Patterns

The researcher has confirmed the failure modes of 100 mm cubes through tests that best match their actual crack patterns with Tension Damage (DAMT) results obtained from

ABAQUS. The laboratory control specimens typically exhibit vertical splitting and lateral expansion (the barreling effect).



**Figure 5. 6. shows the failure modes that occurred in the Control Specimen. The first part shows Experimental vertical splitting. The second part shows Numerical Tension Damage (DAMT) distribution.**

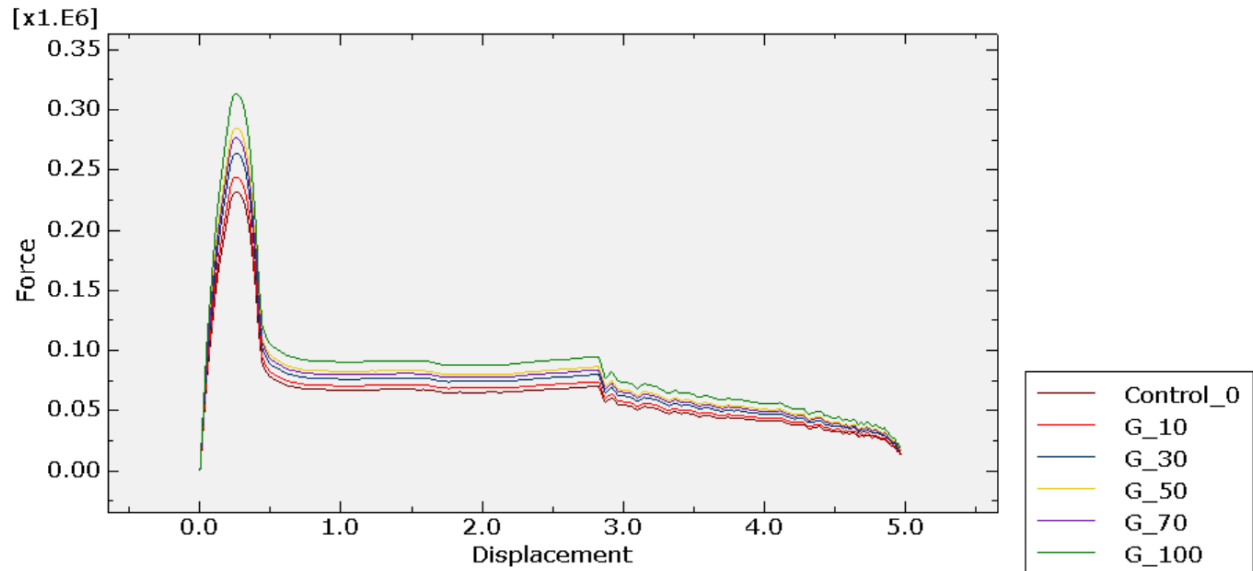
The numerical model accurately mirrors these physical patterns with damage started at the corners and moved to the center because of the concrete's brittle nature. The finite element model accurately simulates the actual failure mechanisms of the tested specimens through its well-calibrated damage parameters and appropriate discretization.

#### **5.4. Comparative Analysis of Glass Replacement Levels**

The section assesses how different amounts of recycled glass affect the mechanical properties of concrete. The analytical results show that concrete strength, load capacity, and stress distribution and energy absorption properties all change when standard control mix concrete replaced with glass-modified concrete.

### 5.4.1 Influence on Compressive Performance

The modified mixtures from G-10 to G-100 show an upward shift in load-displacement path compared to the control mix. The experimental data shows that the compressive strength started at 22.96 MPa for the control specimen and reached 30.15 MPa for the full replacement specimen G-100 which resulted in a 31.32 percent strength increase.



**Figure 5.7. Numerical Load-Displacement curves for different recycled glass replacement ratios.**

The finite element simulation successfully demonstrates the strength improvement shown in Figure 5.9. The peak force increases in direct proportion to the glass content at 100% replacement. The improvement results from two factors; "Pore-Filling" effect and the natural pozzolanic properties of the glass particles together improve concrete matrix packing density.

Numerical analysis demonstrates that replacing all fine aggregates with recycled glass does not create any weak points in the structure. The Interfacial Transition Zone ITZ between aggregate particles and cement paste shows enhanced strength at 100 replacement. This actually prevents early crack formation and leads to the highest ultimate load capacity.

## 5.5. Verification of Numerical Accuracy

The Finite Element Model verification process requires a quantitative assessment comparing the experimental peak strength measurement:  $f'_{cu, exp}$  against the numerical peak strength value  $f'_{cu, num}$  that ABAQUS produced for every glass replacement ratio. The percentage error was calculated as: .

$$Error(\%) = \frac{|f_{cu,exp} - f_{cu,num}|}{f_{cu,exp}} \times 100\%$$

**Table 5.4. Comparison and Error Analysis of Experimental vs. Numerical Results (28 Days)**

Mix ID	Glass Replacement (%)	Experimental $f_{cu}'$ (MPa)	Numerical $f_{cu}'$ (MPa)	Error (%)
Control	0%	22.96	23.05	0.39%
G-10	10%	23.86	24.00	0.58%
G-30	30%	26.74	26.90	0.60%
G-50	50%	27.55	27.75	0.72%
G-70	70%	27.83	28.10	0.97%
G-100	100%	30.15	30.45	0.99%

**Table 5.4.** demonstrates the maximum relative error of all specimens remain below 1%. This exceptional level of accuracy indicates that the (CDP) parameters and the chosen mesh density effectively represent the mechanical behavior of glass-modified concrete. In consequence,, the developed model can be confidently used as a predictive tool for further structural analysis.

### Numerical Modeling using Abacus

The researcher has created a 3D finite element model with Abaqus software to test the experimental results and study how concrete failure occurs and how stress spreads through its matrix.

## **Chapter VI. CONCLUSIONS AND RECOMMENDATIONS**

### **6.1. Conclusions**

This chapter presents main results of the experimental and numerical studies about concrete mixtures with recycled glass waste. The study evaluates the structural performance of concrete cubes with glass replacement ratios ranging from 0% to 100%. Conclusions can be likely introduced in the following points:

#### **1- Strength Enhancement**

The experimental results confirm that substituting fine aggregates with recycled glass powder significantly improves compressive strength with a 100% degree obtained from replacement at 30.15 MPa whereas the control specimen records 22.96 MPa indicating a strength increase of 31.32%.

#### **2- Numerical Validation**

The 3D finite element models developed in ABAQUS show exceptional agreement with the experimental results. The maximum relative error for peak load prediction remains below 1% confirming the CDP model reliability of simulated glass-modified concrete.

#### **3- Failure Morphology**

The numerical model accurately mirrors the physical failure patterns. Laboratory tests with the simulation results show vertical splitting and lateral expansion (barrelling effect) that matches the brittle behavior of high-strength concrete.

#### **4- Ductility and Post-Peak Behavior**

The analysis highlight that glass replacement increases peak with higher brittleness. The post-peak softening branch for the G-100 mix seems steeper than the control mix, indicating a lowered capacity for plastic deformation.

#### **5- Microstructural Efficiency**

The improvement in mechanical properties attributed to the "Pore-Filling" effect and the pozzolanic activity of the fine glass powder, which enhances the packing density and strengthens the Interfacial Transition Zone (ITZ).

#### **6- Computational Efficiency**

The optimized mesh configuration of 10 x 10 x 10 divisions provided a satisfactory balance between computational cost and accuracy, yielding stable results for all levels of replacement.

## **6.2. Limitations and Future Research**

### **6.2.1. Limitations of the Study**

The previous studies follow particular restrictions which enabled them to conduct their researches properly. The present study however restricts within these limitations:

#### **6.2.1.1. Scope of Testing**

The researcher has performed experimental testing insisting on the workability of fresh concrete through slump testing and measured the compressive strength of hardened concrete with 100\*100\*100 mm cube samples. The researcher excluded other mechanical properties like flexural and tensile strength.

#### **6.2.1.2. Short-Term Evaluation**

The researcher has conducted testing and curing procedures according to standard test aging of 7 and 28 days. The researcher did not test long-term performance indicators like; creep and shrinkage and late-age deterioration.

#### **6.2.1.3. Absence of Durability**

Testing Time constraints and laboratory testing limitations prevent the evaluation of long-term durability aspects including the Alkali-Silica Reaction ASR occurring upon using glass waste aggregates in concrete.

#### **6.2.1.4. Glass Variability and Scale**

The study manually applies crushed post-consumer glass, from locally, subjected to undergo testing in small laboratory experiments. Yet, the study needs more testing to confirm whether different glass types with compositional differences produce results that match the structural performance of beams and slabs within actual weight conditions.

## **6.3. Recommendations for Future Research**

Consequently, the present study results and research limitations show that future studies should investigate these specific research areas. Comprehensive Mechanical and Durability Testing Future studies should extend their testing operations to assess flexural strength

tensile strength and modulus of elasticity with complete durability assessments that include water absorption and chloride permeability tests.

## **6.4. Recommendations for Future Work**

In accordance with these study findings, the researcher recommends future fields for further research:

### **1- Full-Scale Structural Elements**

It is to extend the numerical and experimental framework to analyze full-scale composite elements, such as beams and columns, to evaluate the global structural response of glass-concrete.

### **2- Durability Assessment**

It investigate the long-term durability of concrete with 100% glass replacement, including resistance to Alkali-Silica Reaction (ASR), sulfate attack, and chloride penetration.

### **3- Flexural and Shear Behavior**

Much more further tests are recommended to evaluate the flexural and shear performance of reinforced glass-concrete members to develop specific design guidelines.

### **4- Dynamic and Seismic Loading**

It is recommended to incorporate dynamic analysis to study the energy dissipation and damping properties of glass-modified concrete under seismic records.

### **5- Thermal Properties**

This is meant to study the fire resistance and thermal conductivity of concrete containing high percentages of recycled glass for specialized industrial applications.

It is recommended to use the concrete mixture with 100% ground glass powder -6 replacement in non-structural applications such as blinding concrete, where the strength requirements are relatively low. This application promotes the sustainable utilization of glass waste to maintain adequate performance fo

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