



Mechanical and durability performance of concrete incorporating waste glass powder and ldpe in saline environments

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Abstract. The depletion of natural sand reserves and the accumulation of plastic and glass waste necessitate sustainable alternatives for concrete production, particularly for infrastructure in aggressive environments such as the Dead Sea region. This study evaluates the mechanical and durability performance of concrete incorporating waste glass powder and Low-Density Polyethylene (LDPE) granules as partial replacements for fine and Coarse aggregates. Experimental mixes included a control sample and variations with 10% glass powder combined with 5%, 10%, and 15% LDPE, subjected to standard curing and 3-month immersion in a 5% NaCl + 5% Na₂SO₄ saline solution. Mechanical properties were assessed through compressive and tensile strength tests, ultrasonic pulse velocity, and strain gauge measurements, complemented by microstructural analysis using SEM and XRF, and numerical validation via ABAQUS Concrete Damage Plasticity (CDP) simulations. Results indicated that the mix containing 10% GP and 5% LDPE showed optimal performance, reached a compressive strength of 46.63 MPa, compared to 42.47 MPa for the control. Notably, after saline exposure, this optimal mix showed a 47.49% strength increase, whereas the control suffered a 13.72% reduction, attributed to the pozzolanic reaction of GP and the hydrophobic barrier effect of LDPE. Microstructural analysis confirmed reduced efflorescence (salt crystallization) and ettringite formation in modified samples, while simulations (Abaqus) validated superior stress redistribution capabilities. These findings demonstrate that combining waste glass and LDPE enhances concrete ductility and resistance to chloride and sulfate attack, offering a viable sustainable solution for infrastructure in corrosive marine environments.

Keywords: glass powder, ultrafine glass powder, fine aggregate replacement, concrete mix optimization, waste glass, durability, superplasticizer, Jordan, polyethylene, coarse aggregate replacement

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1. INTRODUCTION

Concrete comprises cement, fine and coarse aggregates, water [1], and occasionally admixtures [2]. Contemporary construction predominantly favors concrete over brickwork [3], driven by its exceptional workability, mechanical strength, and longevity rather than economic factors alone [4]. Nevertheless, the intensive exploitation of natural sand for fine aggregate has exhausted worldwide sand stocks to unsustainable thresholds [5], inflicting profound ecological harm such as the ruin of riverine and marine ecosystems. Amid these intensifying pressures, the pursuit of environmentally benign replacements for natural sand is of paramount importance. This imperative similarly applies to coarse aggregates, necessitating greener options.

The proliferation of plastic waste constitutes a foremost ecological emergency in the modern era [6]. Prized for their resilience and adaptability [7], plastics nonetheless cause extensive contamination and ecosystem impairment due to mismanagement and protracted decomposition. Global output hit 368 million metric tons in 2019, yet recycling efficacy continues to lag despite prolonged campaigns [8]. A practical approach to sustainability involves turning plastic waste into a resource for construction, particularly concrete. By swapping out some of the standard aggregates for recycled plastic, we can create greener building materials. Various types of plastic waste have been studied for this role, serving as everything from gravel substitutes to fine sand or reinforcing fibers. As coarse aggregates, materials including high-impact polystyrene (HIPS), polyamide (PA), PET chips, polyethylene terephthalate (PET), PET/PE/PP blends, PVC, PP, HDPE, and e-waste components have been employed. In fine aggregate roles, studies have integrated PP/HDPE/PVC mixtures; PET variants such as granules, crushed bottles, and bottle caps; plastics from e-waste; engineered plastic sands; and neat PE or HDPE. Moreover, plastic fibers—derived from waste face masks, conventional and macro-PP fibers, recycled food trays, carpet waste, metallized films, e-waste, PET from bottles or textiles, and HDPE ropes—have been incorporated to bolster concrete's mechanical performance and durability [9]. This multifaceted integration of plastic waste streams into construction mitigates the escalating plastic pollution crisis while fostering sustainable, circular paradigms in building practices.

This study investigates the use of Low-Density Polyethylene (LDPE) waste as a partial replacement for fine aggregate in 40 MPa concrete, evaluating its effects on mechanical and physical properties at replacement levels of 0%, 5%, 10%, 15%, and 20% (with a constant water-cement ratio of 0.4). Results show a consistent decline in strength as LDPE content increases: compressive strength dropped from 42.5 MPa to 25.4 MPa (40.2% reduction), split tensile strength from 3.8 MPa to 2.3 MPa (39.5% reduction), and flexural strength from 5.2 MPa to 3.2 MPa (38.5% reduction). While LDPE reduces concrete strength, it offers a sustainable solution for plastic waste reuse. Its application is most suitable for non-structural or light structural uses, where lower strength requirements align with the material's performance, supporting environmentally responsible construction practices [10].

This investigation examined waste PET straps, shredded into fibers, as concrete reinforcement, with fiber volume fractions ranging from 0% to 0.5% and aspect ratios of 2.5 and 3. Findings revealed enhanced splitting tensile strength, accompanied by marginal declines in compressive strength and workability [11]. Separately, the study assessed low-density polyethylene (LDPE) as a partial sand replacement in M20-grade concrete, employing substitution levels of 0%, 5%, 10%, 15%, and 20% at a water-cement ratio of 0.5. Results indicated a 35–50% reduction in compressive strength relative to the control mix. Notwithstanding this decrement, the modified concrete proves viable for non-structural uses where elevated compressive strength is unnecessary, thereby providing a feasible avenue for plastic waste valorization and sustainable construction [12].

Glass ranks among the most adaptable materials globally, prized for its superior chemical stability, optical transparency, mechanical strength, and impermeability [13]. As industrialization intensifies and living standards elevate, worldwide glass production—and attendant waste generation—has escalated dramatically. In 2017, Chinese urban areas alone produced about 20.255 million tons of waste glass. Although global waste glass recovery averages roughly 50%, China's rate lingers at a mere 20%, leaving approximately 80% unmanaged and destined for landfills or open dumping [14]. Given its chemical inertness, waste glass resists decomposition in landfills, perpetuating the occupation of scarce land. Moreover, contamination with metals, plastics, adhesives, labels, and residues exacerbates risks; prolonged environmental exposure enables leaching of toxicants, threatening water, soil, and air quality [15].

Heightened environmental consciousness has fueled growing research into integrating solid wastes and industrial by-products into concrete formulations. Beyond preserving virgin resources and energy, select waste materials can augment specific concrete properties. For example, substituting waste glass for fine aggregate enhances resistance to chloride ingress, thereby bolstering durability—especially in harsh settings like marine or de-icing salt environments [16].

This experimental study evaluated the pozzolanic reactivity of waste glass powder as a cement substitute at weight replacement ratios of 0%, 15%, 30%, 45%, and 60%. Findings indicated that up to 30% substitution maintained 28-day compressive strength equivalent to the control, attributable to the pozzolanic reaction between glass powder and cement hydration-derived calcium hydroxide. Durability further advanced with escalating glass powder content: chloride ion and water penetration resistance improved steadily, persisting to 60% replacement. At this threshold, electrical resistivity increased by 95%, water penetration depth declined by 80%, and compressive strength retained 85% of the reference value. These gains stemmed from a densified microstructure, particularly in the interfacial transition zone, corroborated by pore size distribution analyses revealing diminished capillary pores that facilitate water and chloride ingress. Remarkably, a modest 15% glass powder addition yielded high-performance concrete with enhanced strength and impermeability, underscoring its role as an active pozzolan rather than a passive filler [17].

This investigation assessed the impact of waste glass powder (WGP) as a partial cement replacement on the flexural behavior of reinforced concrete beams (RCBs). Nine beam specimens incorporated WGP at 0%, 10%, 20%, and 30% by weight of cement, with stirrup spacing varied to evaluate its influence. Optimal performance emerged at 10% WGP substitution; elevated levels—particularly exceeding 10%—diminished load-bearing capacity, especially in beams featuring higher longitudinal reinforcement ratios [18].

The construction sector ranks among the foremost consumers of natural resources and a major generator of global waste. Recent years have witnessed intensified efforts to counter rising plastic pollution and waste glass accumulation through sustainable building material innovations. Plastic waste—enduring, non-biodegradable, and prone to mismanagement—presents profound environmental and health hazards, whereas waste glass, despite its chemical stability and abundance, suffers underutilization amid suboptimal recycling rates in numerous regions [19]. Their incorporation into concrete proffers a compelling strategy: plastic waste serves as a partial natural aggregate replacement, alleviating density and preserving resources, while milled waste glass functions as a pozzolanic cement adjunct or fine aggregate, refining microstructure and durability via its siliceous reactivity. Such dual integration mitigates waste challenges while advancing resource-efficient, eco-friendly concrete formulations [20].

The study emphasizes on incorporating GP and LDPE with quartz sand and quartz stone, the materials were selected for their local abundance in Russia—and because they share similar physical and chemical characteristics with commonly abundance materials in Jordan, where limited research exists on their combined applications in concrete mixtures. While the experimental work was conducted in Russia, the findings are particularly relevant for Jordan, where quartz-based materials are widely available but underutilized in sustainable concrete production. Using locally available materials like recycled plastic could help Jordan cut down on waste while pushing its industries toward greener practices.

This specially formulated concrete could even be used in areas near the Dead Sea—places constantly battered by salty, corrosive winds. That region is incredibly harsh: extreme salt levels and

relentless salt-laden breezes can seep into ordinary concrete, causing crystals to form inside its pores and rust to eat away at the steel reinforcement. Over time, this weakens standard concrete significantly. But with the right design, this eco-friendly mix could stand up to the challenge. To remain durable under these conditions, the mixture should incorporate a low water–cement ratio and supplementary cementitious materials such as glass powder to refine the pore structure, while finely ground glass powder and plastic waste can further reduce permeability and water absorption, thereby limiting ion ingress. When properly proportioned in this way, such a mix significantly mitigate the deleterious effects of saline air currents and maintain its mechanical and durability performance over time in the Dead Sea environment.

2. METHODS AND MATERIALS

The materials used in this experimental study were carefully selected to ensure consistency and reliability in the results.

Cement. Ordinary Portland Cement (OPC) of grade 53= M500 (Russian standard) as shown in the Fig. 1a, was used as the primary binding material. Cement provides the necessary adhesive properties to bind all the constituents of concrete together.

Fine Aggregates. Fractionated quartz sand passing through a 4.75 mm sieve, was used as fine aggregate. The peculiarity of the offered quartz is the presence of coarse-grained sands, with a large fineness modulus up to M 3.5 as shown in the Fig. 1b. Quartz sand has a rounded shape of the part with a low content of clay inclusions and inclusions of soft rocks. The resulting quartz sand undergoes additional enrichment and drying. The moisture content is up to 0.2% Table 1.

Table 1. Comparison of chemical properties of Quartz sand.

Chemical Properties of Quartz sand		
Major oxides	In Jordan (Ras En Naqb) Ministry of Energy and Mineral Resources [21]	In Russia (Crystal Mountain) [22]
SiO ₂	98.7	98.9
Al ₂ O ₃	0.52	0.62
Fe ₂ O ₃	0.04	0.07
Na ₂ O+K ₂ O	0.11	0.105

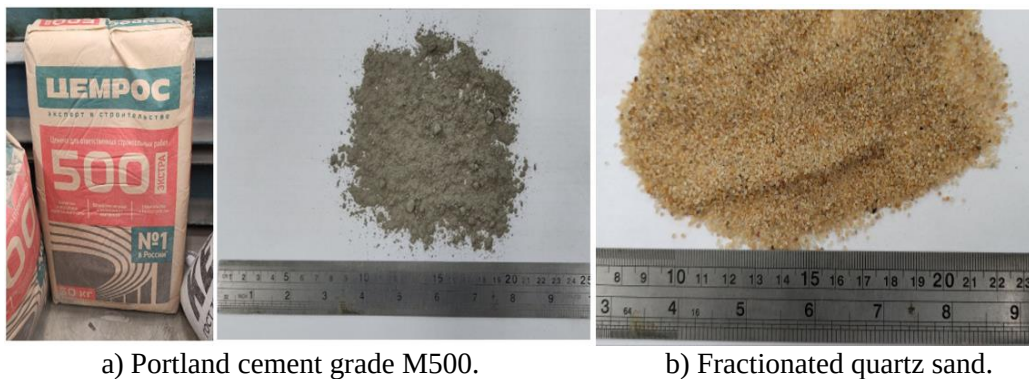


Fig. 1. Fine Materials in Concrete Technology.

Coarse Aggregates. Crushed stone aggregates (vein quartz) with a maximum nominal size of 20 mm were used. The coarse aggregates were well-graded, ensuring optimal packing density and workability of the concrete mix. Vein quartz is represented by grains of acute angles. Unlike river and quarry sands, crushed quartz grains are represented by flat edges with an uneven, rough surface as shown in the Fig. 2a.

Low-Density Polyethylene (LDPE) Plastic Granules. LDPE plastic waste was processed into granules of a specific size range (4-5 mm), to ensure uniform distribution within the concrete mix. The plastic granules were used as a partial replacement for aggregates at varying percentages as shown in the Fig. 3b.



a) Vein quartz with a maximum nominal size of 20 mm. b) The granules of a specific size range (4-5 mm) of LDPE.

Fig. 2. Coarse Materials in Concrete Technology.

Micro glass beads. are tiny spherical glass particles with a diameter of 106-600 μm and 0-50 μm .



Fig. 3. Micro glass beads fraction 106-600 μm and 0-50 μm .

Water. Potable water, free from harmful chemicals and impurities, was used for mixing and curing the concrete samples. The water-cement ratio ($w/c=0.38$) was maintained as per mix design requirements to achieve the desired workability and strength ASTM C187.

Mixing and casting. A drum concrete mixer with an electric motor, a feed chute, and a discharge chute were used for mixing the materials. Compressive strength tests were conducted on cylindrical specimens measuring 150 mm in diameter and 300 mm in height in accordance with ASTM C39/C39M as shown in the Fig. 4. The experimental procedure involved uniform mixing of cement, sand, coarse aggregate, low-density polyethylene (LDPE) granules, and glass powder at a controlled water-cement ratio of 0.38 with superplasticizer as shown in the Table 2. Freshly prepared concrete mix was placed sequentially in three layers into steel forms pre-treated with a release agent, each layer being compacted to ensure proper consolidation. To assess the workability of the concrete mix, a slump test was conducted. Compressive strength, and ultrasonic pulse velocity (UPV) PULSAR-2.1 measurements were also performed as shown in the Fig. 5.

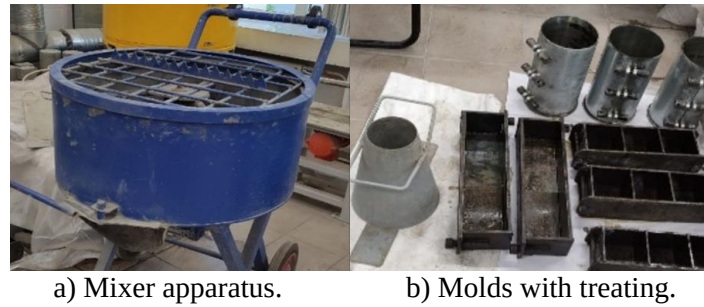


Fig. 4. Mixing and casting.

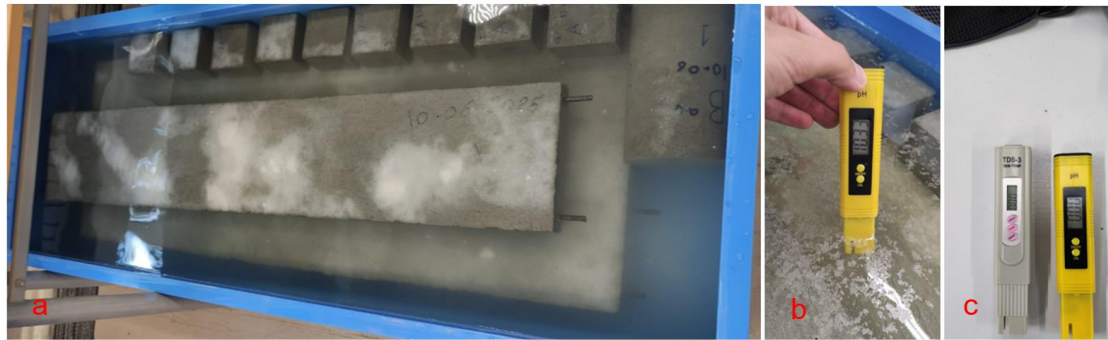


Fig. 5. a) Specimen, b) Testing machine C040PN, c) Ultrasonic device PULSAR-2.1, d) Clever C-31 (also known as RENOM FV), a universal X-ray fluorescence (XRF) spectrometer, e) Specimen.

Table 2. Concrete mix design.

Materials	Mix A	Mix B	Mix C	Mix D
Portland cement	390	390	390	390
Construction sand	897	807.305	807.305	807.305
Coarse aggregate	914	868,3	822.6	776.9
Glass powder 0.106-0.6mm 10%	0	67,275	67,275	67,275
Ultra-fine glass powder 0.0-0.05 mm	0	22.42	22.42	22.42
polyethylene LDPE 5%	0	45.7	91.4	137.1
Water	149	149	149	149
Superplasticizer 1.4%	5.46	5.46	5.46	5.46

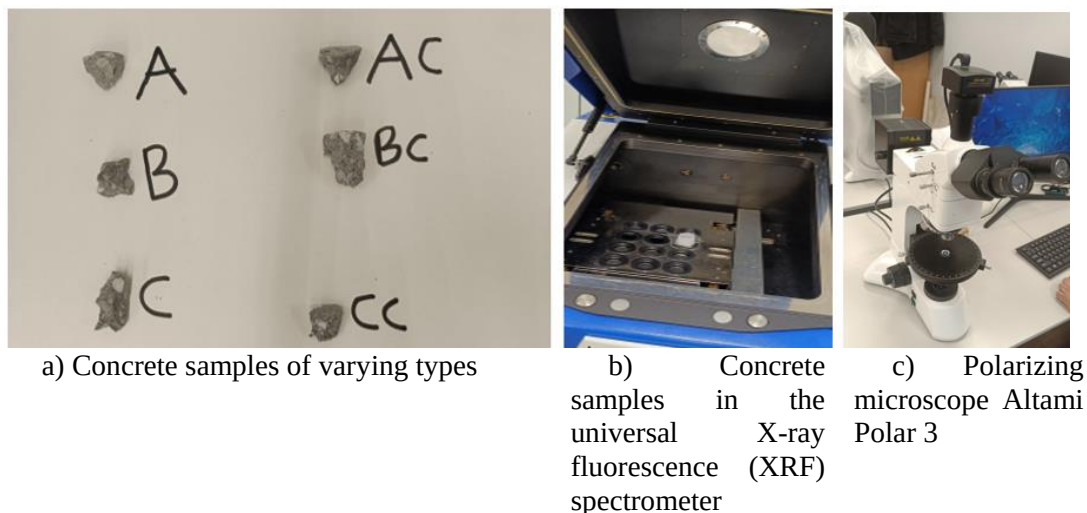
A portion of the samples was immersed in a 5% sodium chloride (NaCl) and 5% Sodium sulphate (Na₂SO₄) saline solution and allowed to age for a period of three months, during which their physical and chemical properties were systematically monitored and recorded at monthly intervals. The deformation has been determined by the using BX120-50AA 120-50AA Gauge concrete (vertical strain gauges are used to measure longitudinal deformations and horizontal strain gauges are used to measure transverse deformations) as shown in the Fig. 6.



a) Samples in a 5% sodium chloride (NaCl & Na_2SO_4) saline solution. b) Determination of PH. c) PH meter and TDS-3 meter (total dissolved solids).

Fig. 6. Curing the specimens by immersion in saline water.

To understand how concrete holds up in harsh, salty environments, we used a precise, non-destructive testing method. The tool of choice was the Clever C-31 (also known as RENOM FV)—a high-tech X-ray spectrometer that can quickly identify and measure multiple elements, from light to heavy, with impressive sensitivity. This made it perfect for tracking how harmful salts like sodium chloride (table salt) and sodium sulfate move into the outer layers of concrete. We carefully collected samples by drilling cores or peeling away thin layers, taking care not to disturb the natural salt patterns. Then, we analyzed the material from the surface down to a depth of 1 centimeter, creating a detailed map of how deeply and aggressively these salts penetrate. At this depth level, the XRF spectrometer was calibrated using. The Clever C-31's high-resolution silicon drift detector (SDD) and optimized excitation geometry facilitated the simultaneous detection of characteristic X-ray emissions from key elements: sodium (Na), chlorine (Cl), sulfur (S), calcium (Ca), silicon (Si), and aluminum (Al). By monitoring the intensity ratios of $\text{Cl}/\text{K}\alpha$ and $\text{S}/\text{K}\alpha$ relative to stable matrix elements (e.g., Ca or Si), penetration profiles for NaCl and Na_2SO_4 were constructed with high spatial resolution. This approach not only identifies the presence of aggressive salts but also enables semi-quantitative estimation of their concentration gradients as a function of depth. As shown in the Fig. 7.



a) Concrete samples of varying types b) Concrete samples in the universal X-ray fluorescence (XRF) spectrometer c) Polarizing microscope Altami Polar 3

Fig. 7. Non-destructive testing methods.

To connect strain gauges on a cylinder using the Wheatstone bridge method, the wiring and principle are as shown in the Fig. 8 and Fig. 9, specifically tailored for strain gauge measurement on cylinders [23]:

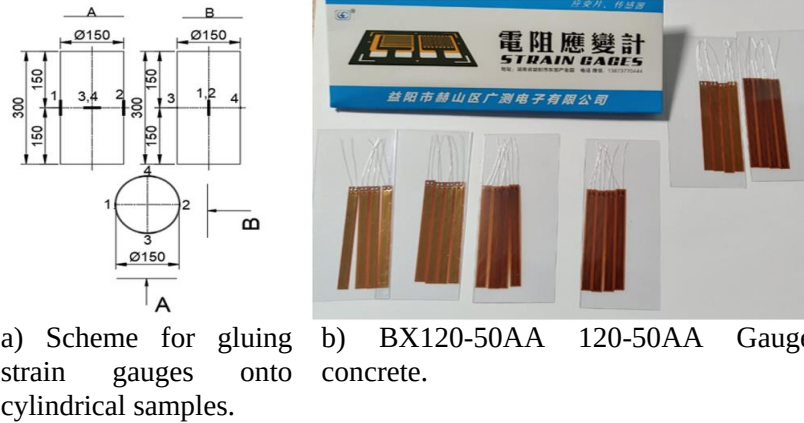


Fig. 8. Wiring and Principle of Strain-Gauge Attachment on a Cylinder.

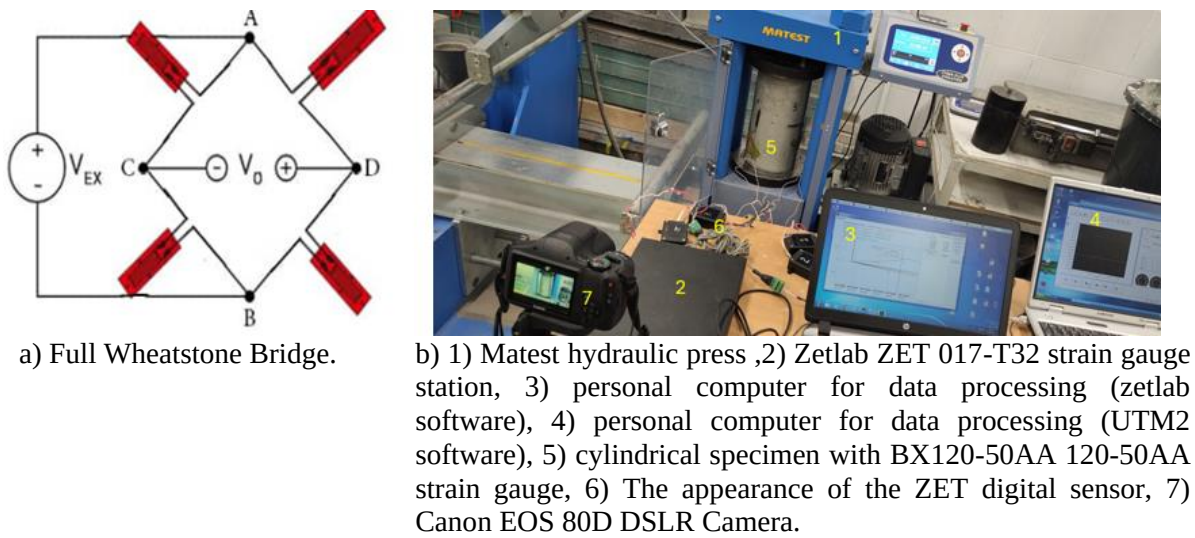


Fig. 9. General view of the experiment.

Full Wheatstone Bridge Equations

1. Balanced Bridge Condition (no strain applied):

$$\frac{R_1}{R_4} = \frac{R_2}{R_3}, \quad (1)$$

when balanced, output voltage V_0 is:

$$V_0 = 0. \quad (2)$$

2. Output Voltage of Full Wheatstone Bridge with strain:

When strain causes changes ΔR_i in each resistor R_i , the output voltage is:

$$V_0 = \frac{V_{ex}}{4} \times \left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4} \right). \quad (3)$$

Gauge Factor and Strain Relation:

The relative change in resistance $\frac{\Delta R}{R}$ is related to mechanical strain ϵ by the gauge factor k

$$\frac{\Delta R_i}{R_i} = k \times \epsilon_i \quad (4)$$

Substituting this in:

$$V_0 = \frac{V_{ex}}{4} \times k \times (\epsilon_1 - \epsilon_2 + \epsilon_3 - \epsilon_4) \quad (5)$$

3. Simplified Output Voltage for Symmetric Strain:

If the strains are symmetric and balanced such that $(\epsilon_1 = \epsilon_3 = \epsilon \text{ and } \epsilon_2 = \epsilon_4 = -\epsilon)$ (common in bending), then:

$$V_0 = \frac{V_{ex}}{4} \times k \times (\epsilon - (-\epsilon) + \epsilon - (-\epsilon)) = V_{ex} \times k \times \epsilon \quad (6)$$

Concrete Damage Plasticity (CDP) is a constitutive material model that combines plasticity and damage mechanics theories to simulate the nonlinear, anisotropic, and quasi-brittle behavior of concrete under various loading conditions such as compression, tension, and shear. It models the cracking, softening, and gradual deterioration of concrete by incorporating both irreversible plastic deformations and stiffness degradation due to damage [24-26].

Concrete Damaged Plasticity (CDP) model.

Concrete inherently features microscopic flaws like tiny cracks and pores – known as initial "damage"—even prior to applying external forces. Failure occurs as these defects grow and multiply across different length scales. The observed nonlinearity in stress-strain curves largely arises from the expansion of these micro-cracks[27]. Concrete's loss of rigidity ties closely to plastic straining, encompassing both tiny-scale processes such as crack widening and flaw progression, and larger-scale effects like particle sliding and bulk flow. An effective material law must therefore integrate elastic damage effects with plastic flow using an elastic-plastic damage framework [28].

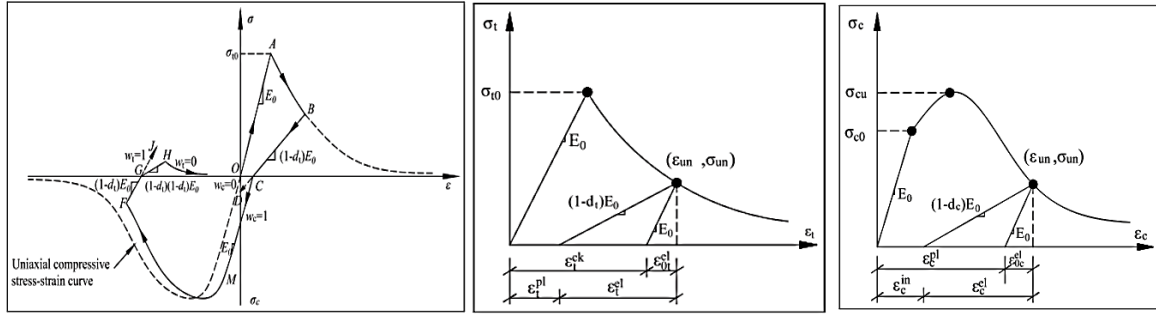
Rather than delving into atomic-level details, engineers model concrete as a uniform, direction-independent continuum. This simplification enables analysis of its overall breakdown and distortion patterns. Finite element implementations of the CDP model extend the pioneering work of Lubliner et al. by merging isotropic damage mechanics with separate plasticity for tension and compression, capturing the full range of nonlinear responses. Damage is presumed equal in all orientations, ideal for complex or reversing load histories. The approach models reductions in elastic rigidity from plastic straining in tension or compression, plus partial stiffness regain during load cycles [29].

In elastic stage, the CDP model adopts the elastic model to describe the mechanical properties of materials. After stepping into the stage of damage, the relation between the elastic modulus in the CDP model can be described as

$$E = (1 - d)E_0, \quad (7)$$

where E_0 indicates the initial elastic modulus, d indicates the plastic-damage factor d_t or d_c in tension or compression and ranges from 0 to 1, in which 0 indicates that the material is not damaged and 1 indicates that the strength of the material is completely lost.

CDP model under uniaxial cyclic loading.



a) Schematic representation of elastic modulus recovery in concrete during tension-to-compression stress reversal. b) Tensile stress-strain curve of CDP model. c) Compressive stress-strain curve of CDP model.

Fig. 10. Concrete Damage Plasticity (CDP) model under uniaxial.

Fig. 10a illustrates the elastic modulus recovery in the Concrete Damage Plasticity (CDP) model under uniaxial cyclic loading—tension → compression → tension again. The behavior is governed by two weighting factors:

$w_t=0$: no tensile stiffness recovery when reloading from compression to tension

$w_c=1$: full compressive stiffness recovery when reloading from tension to compression

Under tension, concrete stiffens until peak stress at point A, where cracking initiates. Further loading to point B causes softening—the effective stiffness reduces to $E = (1 - d_t)E_0$, where d_t is the tensile damage factor. Unloading from B follows path BC, with slope $(1 - d_t)E_0$

Upon reversal to compression:

If $w_c=0$ (no recovery from prior tensile damage), loading proceeds along CD.

If $w_c=1$ (full recovery), it follows the stiffer path CMF.

CDP model under single uniaxial tension/compression.

As to the tensile stress-strain curve of concrete, the data which exceed the range of the elastic part will be entered into the finite element software (Abaqus) [30] with the form of $\sigma_t - \varepsilon_t^{ck}$. The tensile cracking strain is defined as the total strain minus the elastic strain of the material, which is shown in Fig. 10a.

In Fig. 10b, ε_{un} and σ_u denote the strain and stress at the unloading point, respectively, while ε_{0t}^{el} and ε_t^{el} represent the tensile elastic strain of undamaged and damaged concrete, respectively. The symbols ε_t^{pl} and ε_t^{ck} indicate the tensile plastic strain and tensile cracking strain of concrete, respectively.

The tensile damage data are input into Abaqus in the form $d_t - \varepsilon_t^{ck}$, and the program automatically converts the cracking strain into plastic strain using the following formula.

$$\varepsilon_t^{el} = \varepsilon_t^{ck} - \frac{d_t}{1 - d_t} \frac{d_t}{E_0} \quad (8)$$

If the plastic strain ε_t^{el} is negative or the cracking strain ε_t^{ck} is sufficiently small—indicating an intersection of the tensile unloading path—the Abaqus will show an error warning, as tensile damage cannot occur when ε_t^{el} equals ε_t^{ck} . Regarding the compressive stress-strain curve, data points exceeding the elastic range will be treated as inelastic deformation.

The data is input into Abaqus as σ_c versus ε_t^{in} . The compressive cracking strain is defined as the total strain minus the elastic strain calculated under undamaged material conditions, as illustrated in Fig. 10c.

The data of the compressive damage will be entered into the finite element software (Abaqus) with the form of $d_c - \varepsilon_c^{in}$. Then, the program will automatically convert the cracking strain into plastic strain according to the following formula.

$$\varepsilon_c^{pl} = \varepsilon_c^{in} - \frac{d_c}{1 - d_c} \frac{\sigma_c}{E_0} \quad (9)$$

Simplified Damage Plasticity Model for Concrete

The concrete damaged plasticity (CDP) model employs isotropic damaged elasticity coupled with isotropic plasticity in both tension and compression to capture the inelastic behavior of concrete. Within this framework, the total strain tensor ε is decomposed into an elastic component ε^{el} and a plastic component ε^{pl} , such that:

$$\varepsilon = \varepsilon^{pl} + \varepsilon^{el}, \quad (10)$$

$$\sigma = D^{el} : (\varepsilon - \varepsilon^{pl}), \quad (11)$$

$$\bar{\sigma} = D_0^{el} : (\varepsilon - \varepsilon^{pl}), \quad (12)$$

$$D^{el} = (1 - d) D_0^{el}. \quad (13)$$

The nominal (or Cauchy)[31] stress tensor, evaluated through the constitutive relation employing the damage-dependent degraded elastic stiffness tensor as formulated in Equation (13), may be equivalently reformulated in terms of the effective stress concept. This representation explicitly incorporates the coupled effects of isotropic damage evolution in both tension and compression, thereby accounting for the progressive reduction in material stiffness as microcracking and crushing mechanisms develop under increasing mechanical loading. The resulting expression provides a thermodynamically consistent framework for capturing the nonlinear stress–strain response of quasi-brittle materials such as concrete, where the nominal stress is diminished relative to the effective undamaged stress state in proportion to the current damage level.

$$\sigma = (1 - d) D_0 : (\varepsilon - \varepsilon^{pl}). \quad (14)$$

The damage plasticity constitutive model was based on the following stress–strain relationship:

$$\sigma = (1 - d) \cdot \bar{\sigma} \rightarrow \sigma(1 - d_t) \bar{\sigma}_t + (1 - d_c), \quad (15)$$

where d_t and d_c represent two independent scalar damage variables that quantify the progressive degradation of material stiffness in tension and compression, respectively. These variables are constrained to the closed interval [0, 1], wherein a value of 0 corresponds to an intact, undamaged material state with full load-carrying capacity, while a value approaching 1 signifies a fully damaged state characterized by substantial stiffness loss—ultimately representing a completely fractured condition in tension or a crushed state in compression. The concrete damage model, formulated within the theoretical framework of continuum damage mechanics coupled with plasticity theory, explicitly captures the two dominant failure modes observed in concrete structures under mechanical loading: tensile cracking, which manifests as the propagation of discrete cracks under tensile stresses or bending moments, and compressive crushing, which occurs as a result of microcracking, crack coalescence, and volumetric compaction under high confining pressures or uniaxial compression. The model captures concrete's asymmetric response by coupling plastic hardening with damage cracking. Total strain breaks down into elastic, plastic, and cracking components, splitting plasticity between tension and compression to match quasi-brittle behavior. Rather than relying on standard softening, cracking strain acts as residual deformation that drives hardening. This handles stiffness degradation and permanent strain more realistically, especially under cyclic loading where microcracking and plastic flow overlap.

$$\begin{aligned}\varepsilon^{pl,h} &= \begin{bmatrix} \varepsilon_t^{pl,h} \\ \varepsilon_c^{pl,h} \end{bmatrix}; \varepsilon^{pl} = h(\varepsilon^{pl,h}, \bar{\sigma}). \dot{\varepsilon}^{pl} \\ \dot{\varepsilon} &= \dot{\varepsilon}^{el} + \dot{\varepsilon}^{pl}\end{aligned}\quad (16)$$

The uniaxial compressive and tensile stress–strain responses of concrete were defined within the Concrete Damage Plasticity (CDP) model under monotonic compression and tension loading and the effective uniaxial stress.

$$\begin{aligned}\sigma_t &= (1 - d_t)E_0(\varepsilon_t - \varepsilon_t^{pl,h}) \\ \sigma_c &= (1 - d_c)E_0(\varepsilon_c - \varepsilon_c^{pl,h}) \\ \bar{\sigma}_t &= \frac{\sigma_t}{(1 - d_t)} = (\varepsilon_t - \varepsilon_t^{pl,h}) \\ \bar{\sigma}_c &= \frac{\sigma_c}{(1 - d_c)} = (\varepsilon_c - \varepsilon_c^{pl,h}) \\ \varepsilon_c &= \varepsilon_c^{pl,h} + \varepsilon_c^{el} \\ \varepsilon_t &= \varepsilon_t^{pl,h} + \varepsilon_t^{el}\end{aligned}\quad (17)$$

Finite Element Modeling in Python

To support the experimental study, a custom finite element method (FEM) program named CDP-FEM Studio was developed in Python to simulate the behavior of concrete cylinder specimens containing glass powder (GP), ultra-fine glass powder (UFGP), and low-density polyethylene (LDPE) under uniaxial compression. The model employed a smooth swept hexahedral mesh to analyze stress distribution, displacement, and potential failure behavior. A linear elastic constitutive model was implemented in the analysis. This Python-based FEM framework offered a simple and efficient alternative to commercial software for analyzing compression in concrete specimens.

Geometry Parameterization & Mesh Generation

Consider a cylinder of radius R and height H . The axis is aligned with the z -direction ($0 \leq z \leq H$).

A smooth swept hexahedral mesh is created by:

1. Meshing the circular cross-section (at $z = 0$ or $z = H$) with a structured quadrilateral mesh using an O-grid
2. Sweeping (extruding) that 2D mesh along the z -axis to form 3D hexahedral elements

O-grid Mapping for the Cross-Section

Divide the circular disk into five regions: a central square and four curved side patches.

Let the square half-side be $a = R/\sqrt{2}$. Then each quadrant of the circle is mapped from a unit square $(\xi, \eta) \in [-1, 1]^2$ to physical coordinates (x, y) using a transfinite interpolation that preserves orthogonality at the boundary.

Node coordinates for a given quadrant (e.g., first quadrant $x \geq 0, y \geq 0$):

For a grid with n_r divisions in the radial direction and n_θ divisions circumferentially:

Radial coordinate :

$$r(\xi) = a + (R - a) \cdot \frac{\xi + 1}{2}, \quad \xi \in [-1, 1] \quad (18)$$

Angular coordinate:

$$\theta(\eta) = \frac{\pi}{2} \cdot \frac{\eta + 1}{2}, \quad \eta \in [-1, 1] \quad (19)$$

then:

$$x = r(\xi)\cos\theta(\eta), y = r(\xi)\sin\theta(\eta). \quad (20)$$

For the central square ($0 \leq x \leq a$, $0 \leq y \leq a$):

$$x = a \cdot \frac{\xi + 1}{2}, \quad y = a \cdot \frac{\eta + 1}{2}, \quad \xi, \eta \in [-1, 1] \quad (21)$$

This square is later subdivided into quads.

By mirroring and rotating the quadrant mapping, the entire circle is covered with a conforming all-quadrilateral mesh of N_{nodes} points.

Sweeping Along the Axis

The 2D quadrilateral mesh is extruded in the z-direction. Let there be n_z divisions along the height

For each layer $k = 0, \dots, n_z$:

$$z_k = \frac{k}{n_z} H \quad (22)$$

Each 2D quadrilateral (with four corner nodes) becomes a hexahedral element by connecting it to the corresponding quadrilateral in the next layer.

Node numbering:

Let (i, j) index the nodes on the cross-section (after O-grid). Then the 3D node coordinates are:

$$x_{i,j,k} = (x_{i,j}, y_{i,j}, z_k), \quad (23)$$

where $(x_{i,j}, y_{i,j})$ are the pre-computed cross-section coordinates.

Apply a Laplacian smoothing to the 3D mesh nodes (excluding boundaries) to improve aspect ratios and reduce skewness:

$$x_{new} = x + \lambda \sum_{neighbor} (x_{neighbor} - x), \quad (24)$$

With $\lambda \in (0, 1)$ (e.g., 0.5) and iterating a few times.

Finite Element Formulation for 8-Node Hexahedron

An isoparametric formulation has been used. Each element has 8 nodes. Natural coordinates

$$(\xi, \eta, \zeta) \in [-1, 1]^3. \quad (25)$$

Shape Functions

$$N_i(\xi, \eta, \zeta) = \frac{1}{8} (1 + \xi_i \xi)(1 + \eta_i \eta)(1 + \zeta_i \zeta), \quad (26)$$

where ξ_i, η_i, ζ_i are the nodal coordinates in the natural space (± 1).

Strain-Displacement Matrix B

The displacement field is

$$u(\xi, \eta, \zeta) = \sum_{i=1}^8 N_i u_i. \text{ Strains } \varepsilon = B u^e \text{ with}$$

$$B_i = \begin{bmatrix} \frac{\partial N_i}{\partial x} & 0 & 0 \\ 0 & \frac{\partial N_i}{\partial y} & 0 \\ 0 & 0 & \frac{\partial N_i}{\partial z} \\ \frac{\partial N_i}{\partial y} & \frac{\partial N_i}{\partial x} & 0 \\ 0 & \frac{\partial N_i}{\partial y} & \frac{\partial N_i}{\partial z} \\ \frac{\partial N_i}{\partial z} & 0 & \frac{\partial N_i}{\partial x} \end{bmatrix} \quad (27)$$

Spatial derivatives are obtained from the Jacobian J of the mapping $(\xi, \eta, \zeta) \rightarrow (x, y, z)$:

$$\begin{bmatrix} \frac{\partial N_i}{\partial x} \\ \frac{\partial N_i}{\partial y} \\ \frac{\partial N_i}{\partial z} \end{bmatrix} = J^{-1} \begin{bmatrix} \frac{\partial N_i}{\partial \xi} \\ \frac{\partial N_i}{\partial \eta} \\ \frac{\partial N_i}{\partial \zeta} \end{bmatrix}, J = \sum_{i=1}^8 \begin{bmatrix} \frac{\partial N_i}{\partial \xi} x_i & \frac{\partial N_i}{\partial \xi} y_i & \frac{\partial N_i}{\partial \xi} z_i \\ \frac{\partial N_i}{\partial \eta} x_i & \frac{\partial N_i}{\partial \eta} y_i & \frac{\partial N_i}{\partial \eta} z_i \\ \frac{\partial N_i}{\partial \zeta} x_i & \frac{\partial N_i}{\partial \zeta} y_i & \frac{\partial N_i}{\partial \zeta} z_i \end{bmatrix} \quad (28)$$

Constitutive Matrix D (Isotropic Linear Elasticity)

For Young's modulus E and Poisson's ratio ν :

$$D = \frac{E}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1-\nu & \nu & \nu & 0 & 0 & 0 \\ \nu & 1-\nu & \nu & 0 & 0 & 0 \\ \nu & \nu & 1-\nu & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1-2\nu}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1-2\nu}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1-2\nu}{2} \end{bmatrix} \quad (29)$$

Element Stiffness Matrix

$$K^e = \int_{-1}^1 \int_{-1}^1 \int_{-1}^1 B^T D B \det(J) d\xi d\eta d\zeta \quad (30)$$

Using 2×2×2 Gaussian quadrature:

$$K^e \approx \sum_g w_g B^T(\xi_g, \eta_g, \zeta_g) D B(\xi_g, \eta_g, \zeta_g) \det J(\xi_g, \eta_g, \zeta_g). \quad (31)$$

Global System and Displacement Solution

Assemble global stiffness K and load vector F (applied forces, pressures, body loads). Apply boundary conditions (e.g., fixed end at $z=0$, axial tension at $z=H$). Solve:

$$KU = F, \quad (32)$$

where U is the global displacement vector.

Stress Recovery and Failure Analysis

Stress at Gauss Points

At each integration point:

$$\sigma = D\varepsilon = DBu^e, \quad (33)$$

Stress components: $\sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{yz}, \tau_{zx}$.

Principal Stresses

Solve the eigenvalue problem for the stress tensor:

$$\det = \begin{bmatrix} \sigma_x - \sigma_p & \tau_{xy} & \tau_{xz} \\ \tau_{xy} & \sigma_y - \sigma_p & \tau_{yz} \\ \tau_{xz} & \tau_{yz} & \sigma_z - \sigma_p \end{bmatrix} \quad (34)$$

The three eigenvalues $\sigma_1 \geq \sigma_2 \geq \sigma_3$ are the principal stresses.

Failure Criteria

von Mises yield criterion (ductile materials):

$$\sigma_{vm} = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}} \leq \sigma_y, \quad (35)$$

where σ_y is the yield strength.

Maximum principal stress criterion (brittle materials):

$$\max(|\sigma_1|, |\sigma_3|) \leq \sigma_{ult}. \quad (36)$$

Maximum shear stress (Tresca) criterion:

$$\tau_{max} = \frac{\sigma_1 - \sigma_3}{2} \leq \tau_Y. \quad (37)$$

Displacement Magnitude

For any node:

$$u_{mag} = \sqrt{u_x^2 + u_y^2 + u_z^2}. \quad (38)$$

3. RESULTS AND DISCUSSION

Experimental results demonstrate that incorporating waste glass powder and Low-Density Polyethylene (LDPE) influences the compressive strength of composite samples in distinct ways. Sample B (10% glass powder, 5% LDPE) achieved the highest dry compressive strength at 46.63 MPa, surpassing the control Sample A (42.47 MPa). In contrast, higher LDPE concentrations reduced load-bearing capacity: Sample C (10% glass powder, 10% LDPE) recorded 32.81 MPa, and Sample D (10% glass powder, 15% LDPE) fell to 28.70 MPa—representing strength reductions of 22.74% and 32.89% relative to the control. These trends indicate an optimal formulation at the composition of Sample B. Notably, when LDPE content exceeds twice the proportion of glass powder, compressive strength declines markedly as shown in the Fig. 11, underscoring the importance of balanced material ratios for structural applications. Durability testing in an aggressive saline environment (5% NaCl +

5% Na_2SO_4) revealed distinct performance trends across mix designs. Mix B demonstrated exceptional resilience: compressive strength increased by 47.49% relative to baseline, whereas the control sample declined by 13.72%. This improvement arises from two complementary mechanisms: (1) the pozzolanic reaction of waste glass powder, which refines pore structure and densifies the cementitious matrix; and (2) the hydrophobic nature of LDPE, which forms a protective barrier limiting chloride and sulfate ion penetration. Mix C achieved a compressive strength of 35.17 MPa. Notably, even at elevated LDPE levels, the pozzolanic activity of glass powder remained active, providing measurable benefits in corrosive conditions despite the initial strength reduction associated with higher plastic content (Fig. 11).

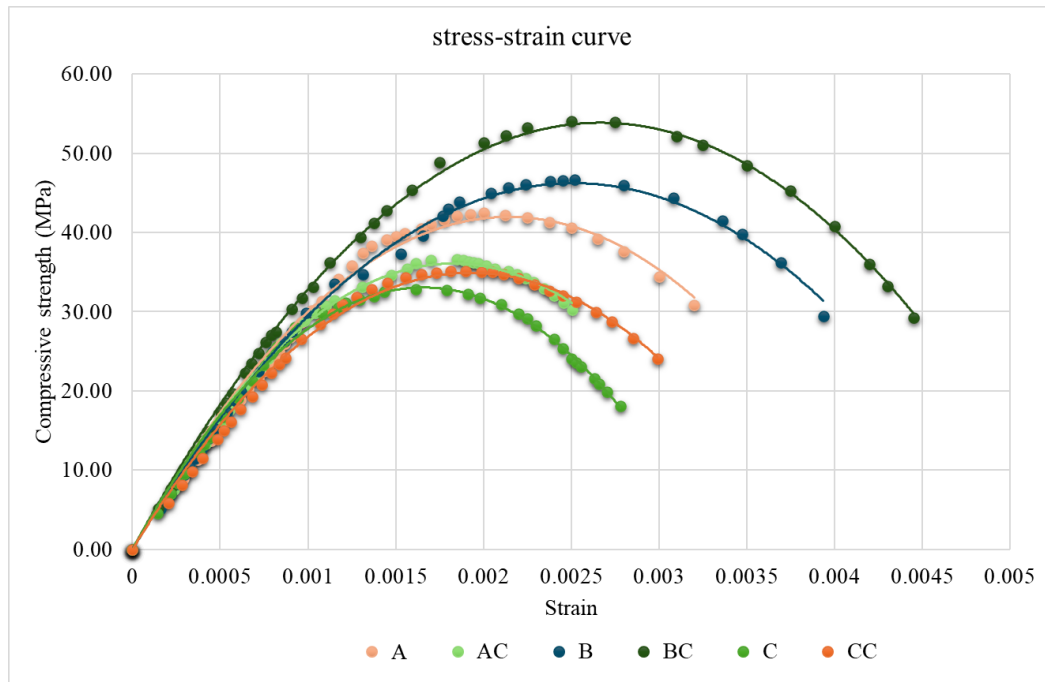


Fig. 11. Stress-Strain curve of all samples.

Tensile testing revealed a clear performance gap between modified composites and the control mix as shown in the Fig. 12. Samples incorporating glass powder and LDPE demonstrated enhanced tensile strain capacity under both dry and saline exposure, indicating that LDPE improves ductility and allows greater deformation prior to failure. Conversely, the control sample exhibited reduced tensile strain capacity, reflecting a more brittle response to tensile loading. This suggests that while the control formulation maintains adequate compressive strength, it lacks the fracture toughness imparted by polymer modification. Consequently, Sample B (10% glass powder, 5% LDPE) emerges as the optimal formulation—delivering high compressive strength and durability alongside improved tensile ductility and resistance to brittle fracture.

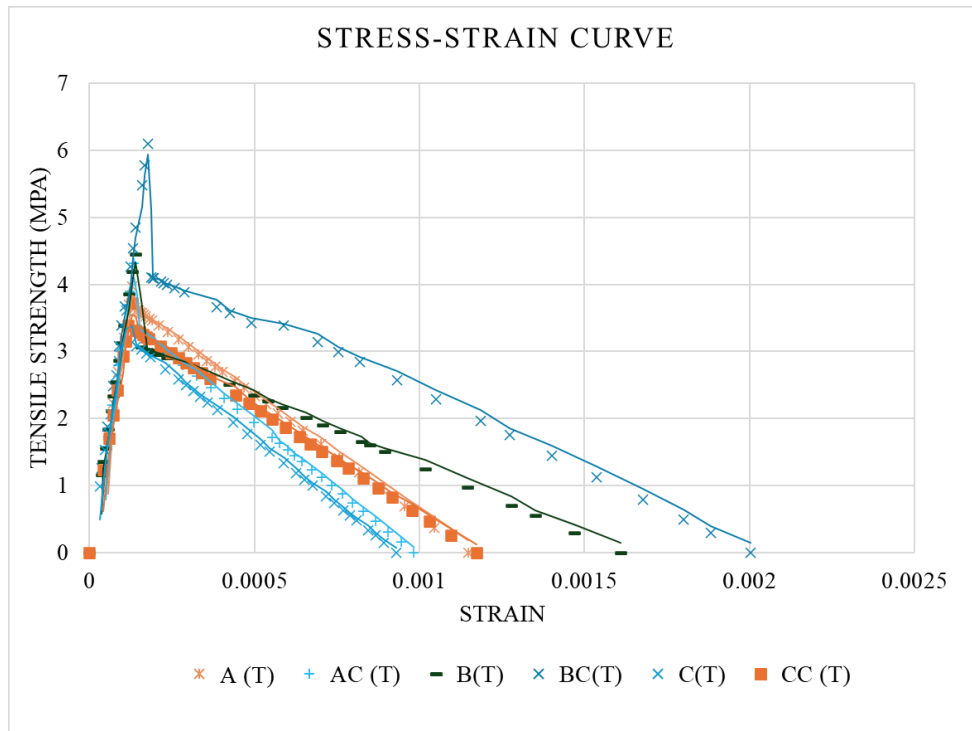


Fig. 12. Stress-Strain curve of all samples.

Fig. (13-15) comprehensive ABAQUS finite element simulation study, utilizing the Concrete Damaged Plasticity (CDP) material model to accurately capture the nonlinear behavior and stiffness degradation of concrete under complex loading scenarios, presents detailed results for cylindrical concrete specimens incorporating sustainable waste materials, where Sample A serves as the baseline control mix with 0% glass and 0% plastic replacement, Sample B introduces 10% glass aggregate and 5% plastic waste, Sample C increases the plastic content to 10% while maintaining 10% glass, and the corresponding AC, BC, and CC samples represent identical mix designs subjected to prolonged exposure to saline water conditions to simulate aggressive marine or coastal environments. The simulation outputs include Von Mises stress distribution contours, which provide a scalar measure of the overall equivalent stress state within each cylindrical specimen under the applied boundary conditions and loading protocol, alongside evolution curves for damage variables in both compression and tension that quantify the progressive loss of material stiffness and load-carrying capacity as microcracking, and macro-cracking develop throughout the loading history. When analyzing the quantitative results, Sample BC (10% glass, 5% plastic, saline exposure) emerges as the optimal composition, demonstrating the highest Von Mises stress value of 7.429×10^1 , which indicates superior stress redistribution capability, enhanced interfacial transition zone bonding between the waste aggregates and cement matrix, and improved overall structural ; furthermore, while BC exhibits elevated damage values in compression (0.4591) and tension (0.952), these remain consistent with expected concrete behavior under the CDP formulation where tensile damage naturally progresses more rapidly due to concrete's inherent brittleness in tension, and critically, the high Von Mises stress suggests that the specimen maintains load-bearing capacity despite this damage evolution. Sample CC (10% glass, 10% plastic, saline exposure) ranks as the second-best performer, showing a moderate Von Mises stress of 4.519×10^1 with comparatively lower compression damage (0.3142) and slightly reduced tension damage (0.9322) relative to BC, which suggests that the higher plastic content (10% versus 5%) introduces greater ductility and energy absorption capacity that helps mitigate damage accumulation, albeit at the cost of reduced overall stiffness and peak stress capacity as reflected in the lower Von Mises value. The comparative performance between BC and CC reveals an important optimization insight: while increasing plastic content enhances ductility and environmental resistance, there appears to be a threshold beyond which the reduction in stiffness and strength outweighs the

benefits of improved toughness, making the 5% plastic formulation in BC the sweet spot for balancing structural performance with sustainability objectives in saline environments. The saline exposure condition, modeled in ABAQUS through adjusted material properties representing chloride-induced degradation, interfacial weakening, and potential expansive reactions, demonstrably influences all damage and stress metrics, yet the BC composition shows remarkable resilience, with its Von Mises stress actually increasing relative to its dry counterpart (Sample B: 6.137 versus BC: 7.429), potentially indicating that the combined glass-plastic aggregate system creates a more tortuous crack propagation path that becomes more effective at redistributing stress when the surrounding matrix experiences salt-induced microstructural changes. From a practical engineering perspective, these ABAQUS simulation results validate the feasibility of incorporating recycled glass and plastic waste into concrete formulations for marine infrastructure applications, with the BC mix design offering a promising pathway to achieve both environmental sustainability through waste valorization and enhanced structural durability in corrosive service conditions, while the detailed damage evolution data provided by the CDP model enables engineers to make informed decisions about safety factors, service life predictions, and maintenance planning for such innovative concrete systems.

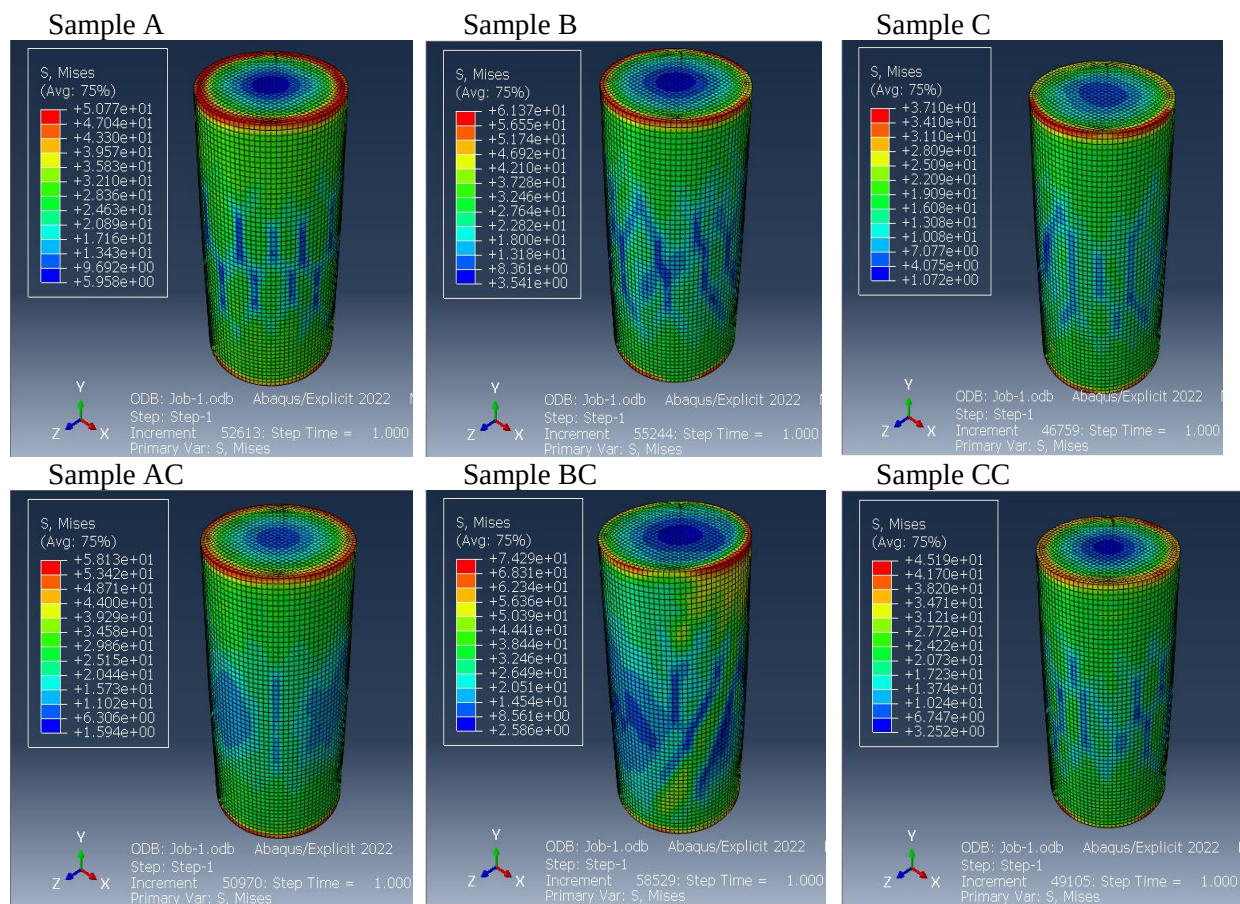


Fig. 13. Von Mises stress distribution in a cylindrical specimen for all mixes.

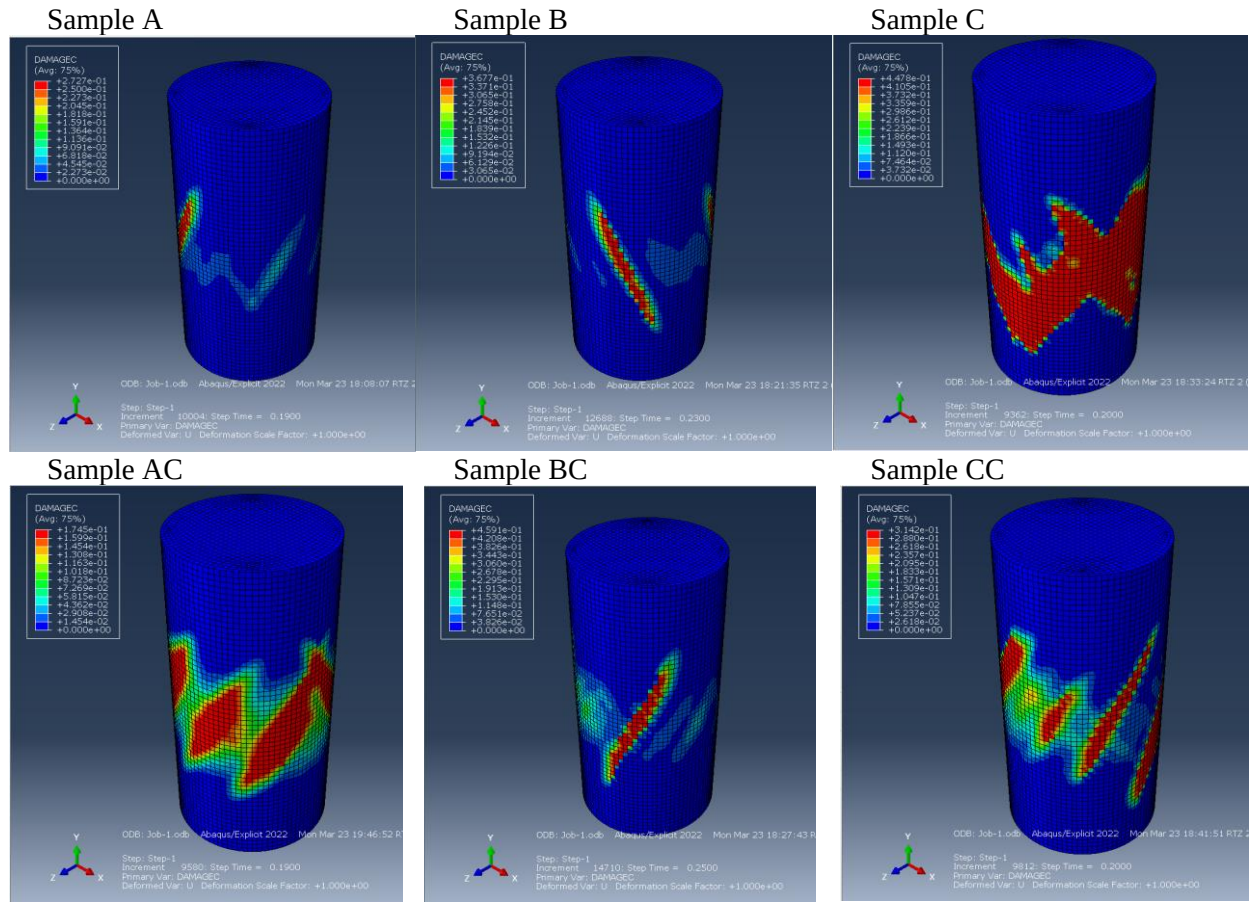


Fig. 14. Damage in compression for all mixes.

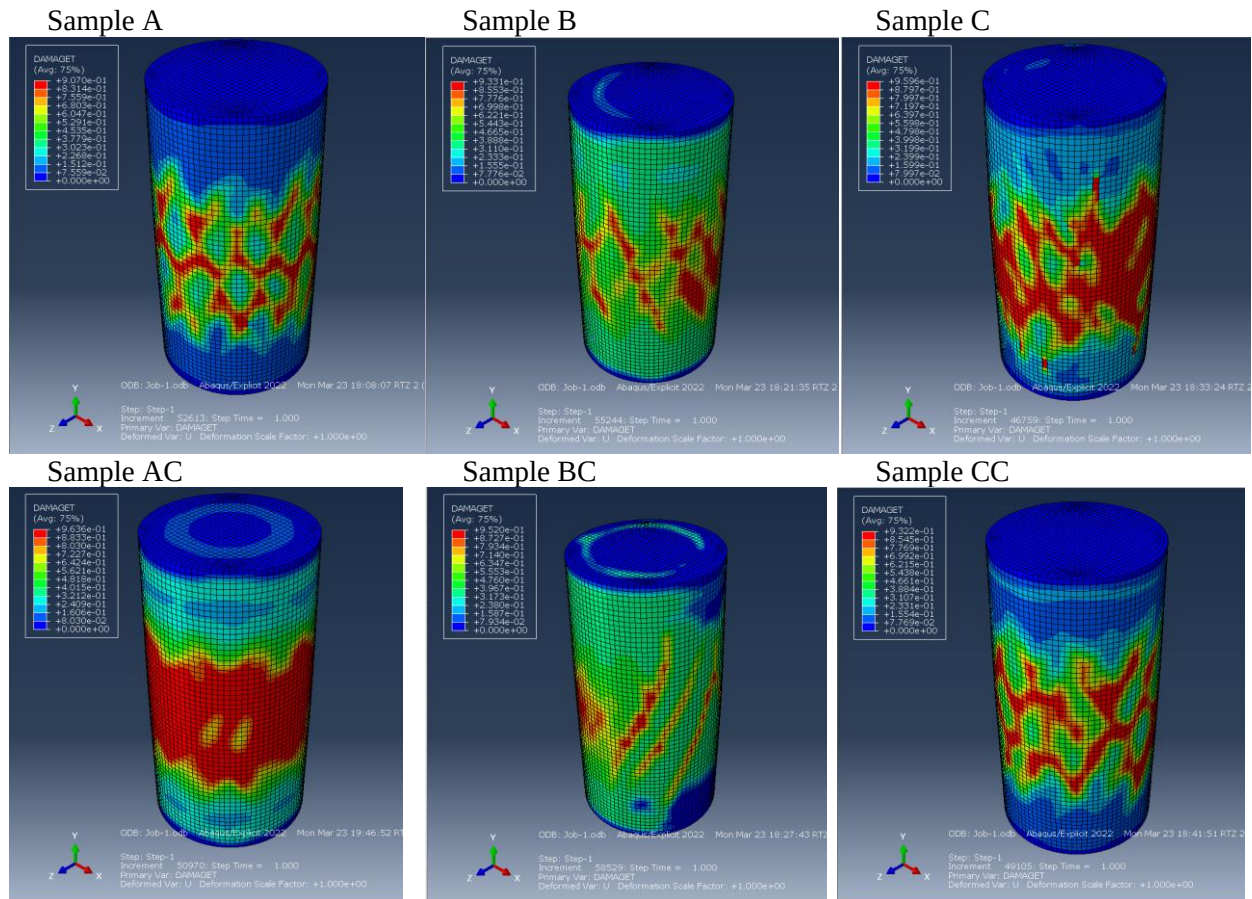
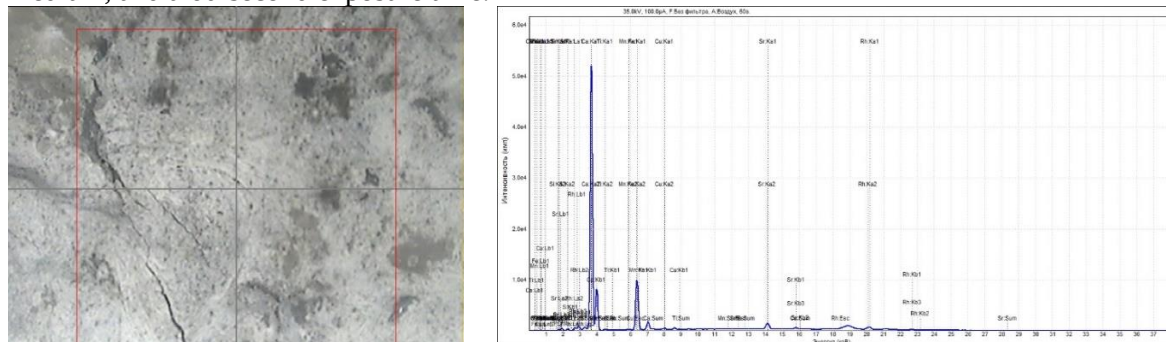


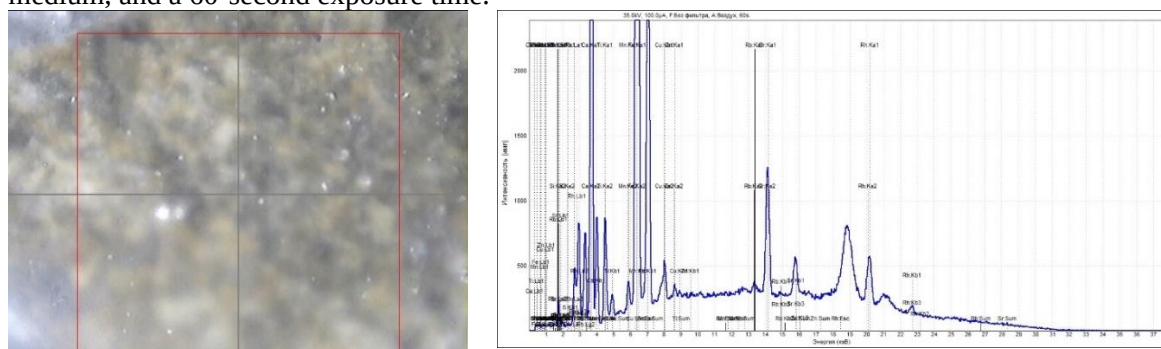
Fig. 15. Damage in tension for all mixes.

As shown in Figure 16, the results of X-ray fluorescence (XRF) analysis for all investigated concrete samples, obtained using a universal X-ray fluorescence (XRF) spectrometer, are presented. The spectra illustrate the elemental composition, including key constituents such as calcium (Ca), silicon (Si), aluminum (Al), and others, highlighting variations due to additives like glass powder or LDPE granules across different mix designs tested under aggressive saline environments.

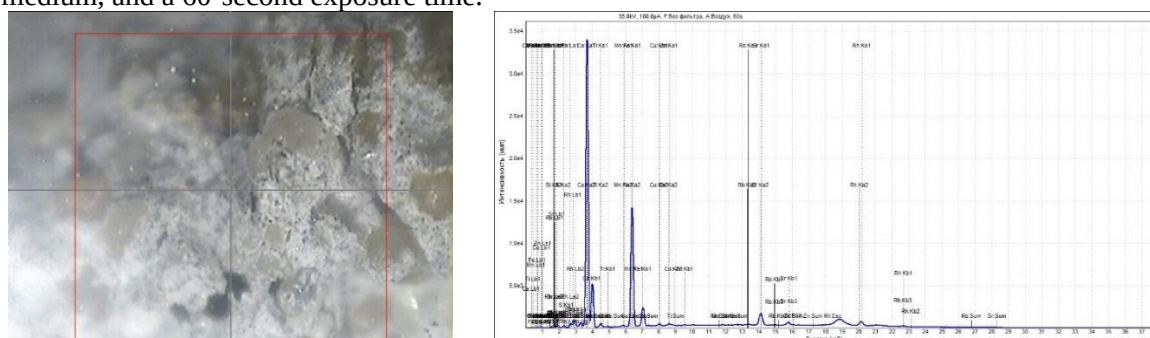
Sample A, 35.0 kV accelerating voltage, 100.0 μ A tube current, no filter applied, air as the medium, and a 60-second exposure time.



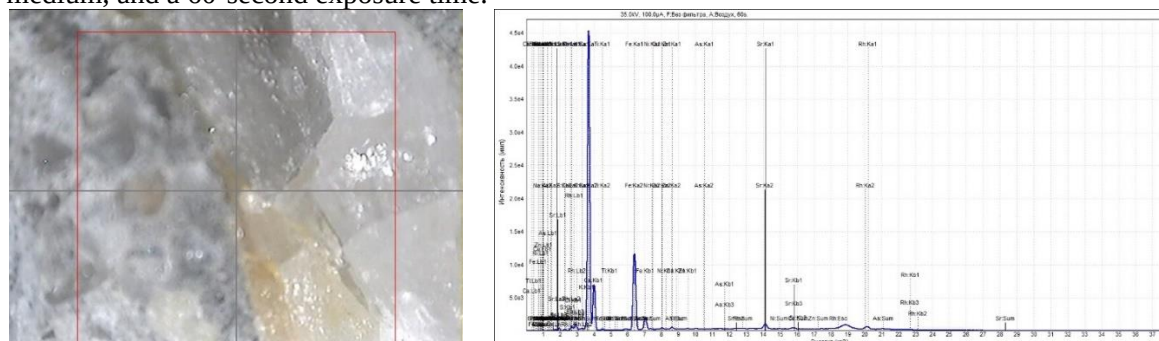
Sample B, 35.0 kV accelerating voltage, 100.0 μ A tube current, no filter applied, air as the medium, and a 60-second exposure time.



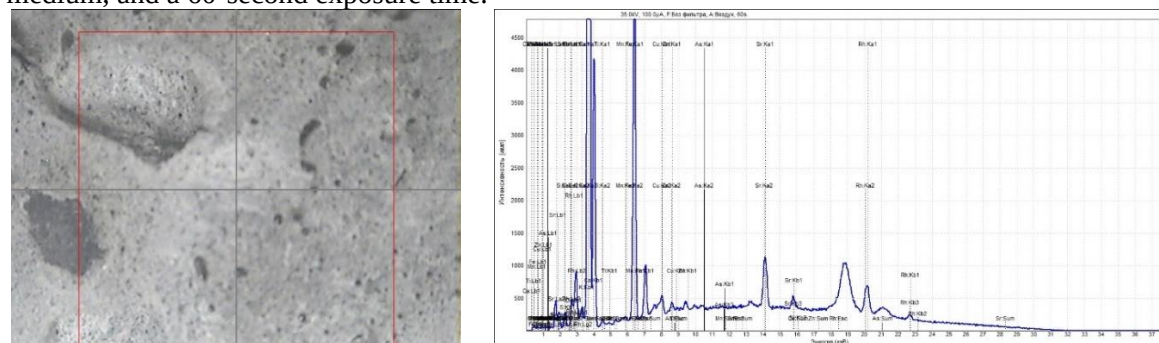
Sample C, 35.0 kV accelerating voltage, 100.0 μ A tube current, no filter applied, air as the medium, and a 60-second exposure time.



Sample AC, 35.0 kV accelerating voltage, 100.0 μ A tube current, no filter applied, air as the medium, and a 60-second exposure time.



Sample BC, 35.0 kV accelerating voltage, 100.0 μ A tube current, no filter applied, air as the medium, and a 60-second exposure time.



Sample CC, 35.0 kV accelerating voltage, 100.0 μ A tube current, no filter applied, air as the medium, and a 60-second exposure time.

Fig. 16. Results of X-ray spectral analysis for all samples.

Fig. 17 show the results of our elemental analysis for the six concrete mixtures tested: A, AC, B, BC, C, and CC. Each figure breaks down the major chemical elements present in a specific mix, making it easy to compare how composition changes across formulations. Together, these visuals offer a clear picture of how adding materials like glass powder or LDPE alters the concrete's chemistry. This chemical insight helps us understand why certain mixes perform better—linking material choices directly to durability, strength, and resistance to environmental damage.

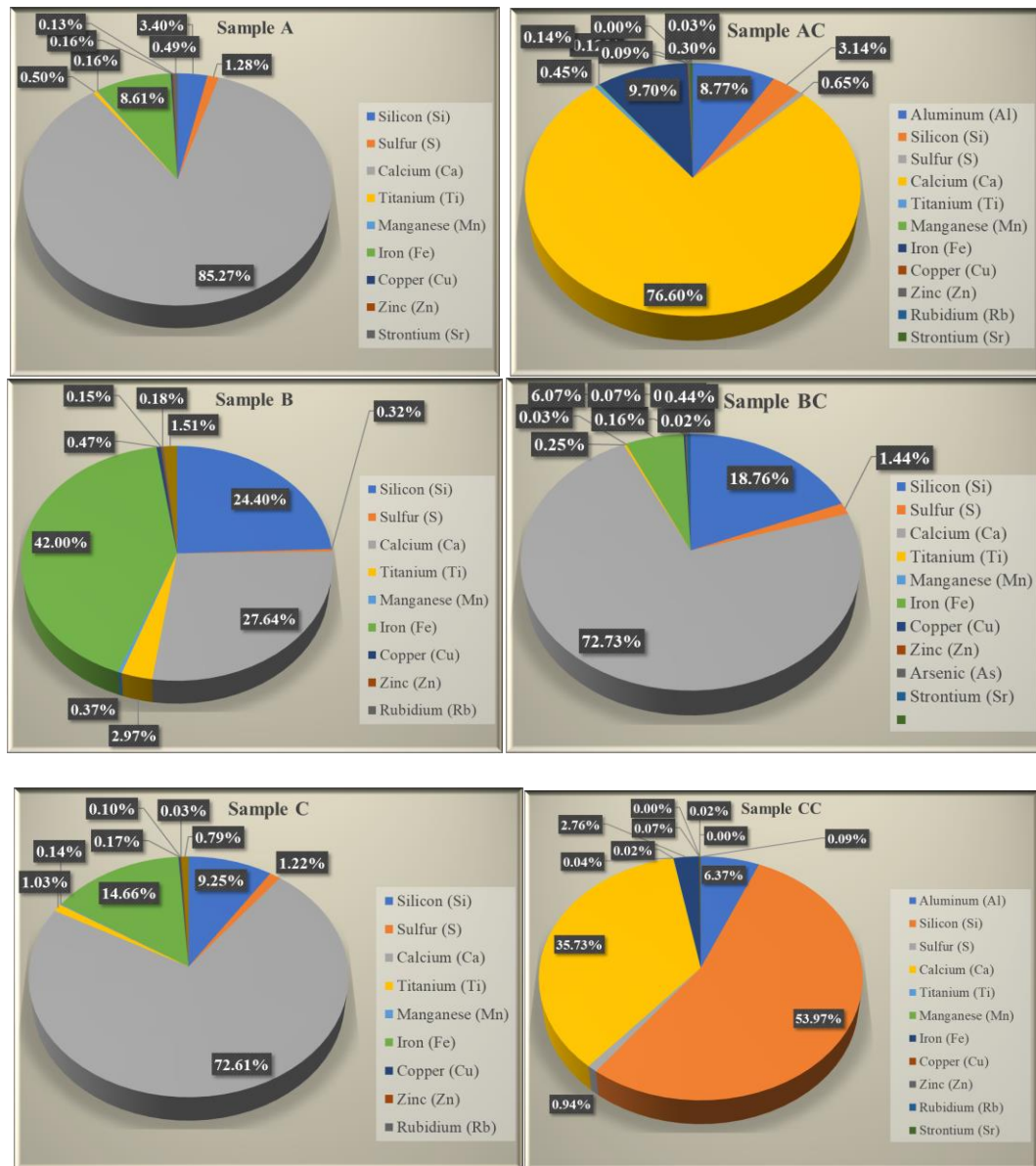


Fig. 17. Element's Concentration for all samples.

The figure 18a presents the ultrasonic pulse velocity (UPV) values for concrete samples A, B, and C, expressed in km/s. Sample A exhibits the highest UPV at 5047.8 km/s, followed by sample B with a UPV of 4963.16 km/s, while sample C shows the lowest value at 4758 km/s, indicating comparatively reduced concrete quality or density for this mix because the pozzolanic reaction has not yet been fully completed. In salty water, however, the pozzolanic reaction can proceed much faster due to the presence of chlorides and the resulting changes in pore solution chemistry; chloride ions in the curing solution can increase the early rate of cement hydration and pozzolanic reactions, enhancing the formation of additional C–S–H gel and refining the pore structure at early ages. The elevated ionic

concentration in saline solutions also increases electrical conductivity and ionic mobility in the pore solution, which promotes the dissolution of portlandite and reactive silica, thereby accelerating the secondary pozzolanic reaction compared with curing in pure water at the same temperature as shown in the Fig. 18.

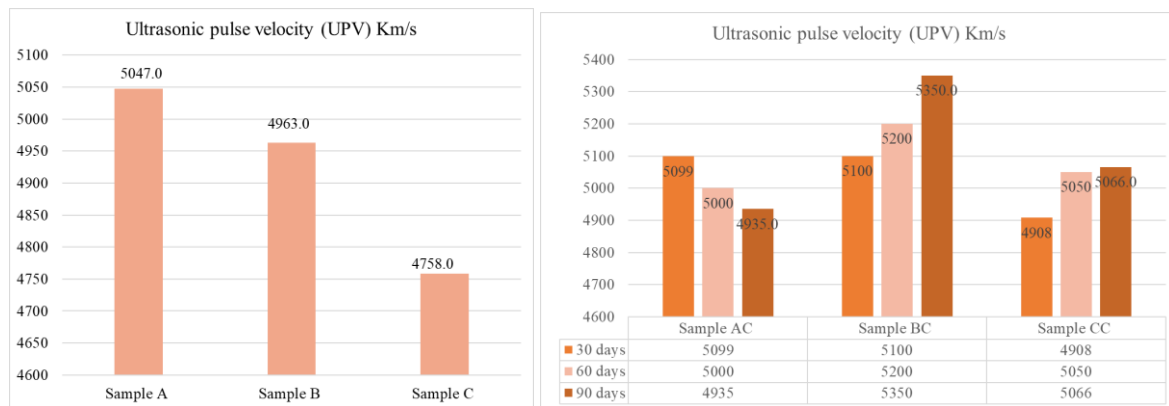


Fig. 18. a) Ultrasonic pulse velocity (UPV) in km/s after 28 days of water curing, b) Ultrasonic pulse velocity (UPV) in km/s after 30, 60, and 90 days of immersion in salty water.

Sample A: The matrix appears relatively dense and uniform, with paste fully filling the spaces around aggregates and minimal visible pores or light "void" spots.

Sample AC: After exposure to salty water, the surface shows greater heterogeneity, featuring more bright/whitish areas corresponding to salt crystals or altered paste, indicative of leaching and early surface deterioration.

Sample B: Incorporating glass powder and plastic reveals numerous small dark and light spots in the paste, indicating dispersed glass particles and plastic inclusions. This increases matrix heterogeneity but refines the pore structure, as the fine glass powder enables pozzolanic reactions.

Sample C: Like Sample B, but with slightly different inclusion distribution and sizing. Depending on dosage and grading, smoother zones form around glass particles (due to pozzolanic reactions), while plastic boundaries appear more distinct (with higher LDPE percentage).

Sample BC: Salty water exposure superimposes brighter specks and patches onto the heterogeneous matrix of Sample B, indicating salt deposition in pores without evident microcracking around inclusions. However, the dense glass-powder-modified paste limits deep penetration.

Sample CC: Displays a similarly refined yet speckled texture. With higher LDPE content in mix C, a denser interfacial transition zone and fewer large voids result, so Sample CC exhibits less obvious damage or leaching than Sample AC, suggesting superior resistance to saline attack as shown in the Fig. 19.

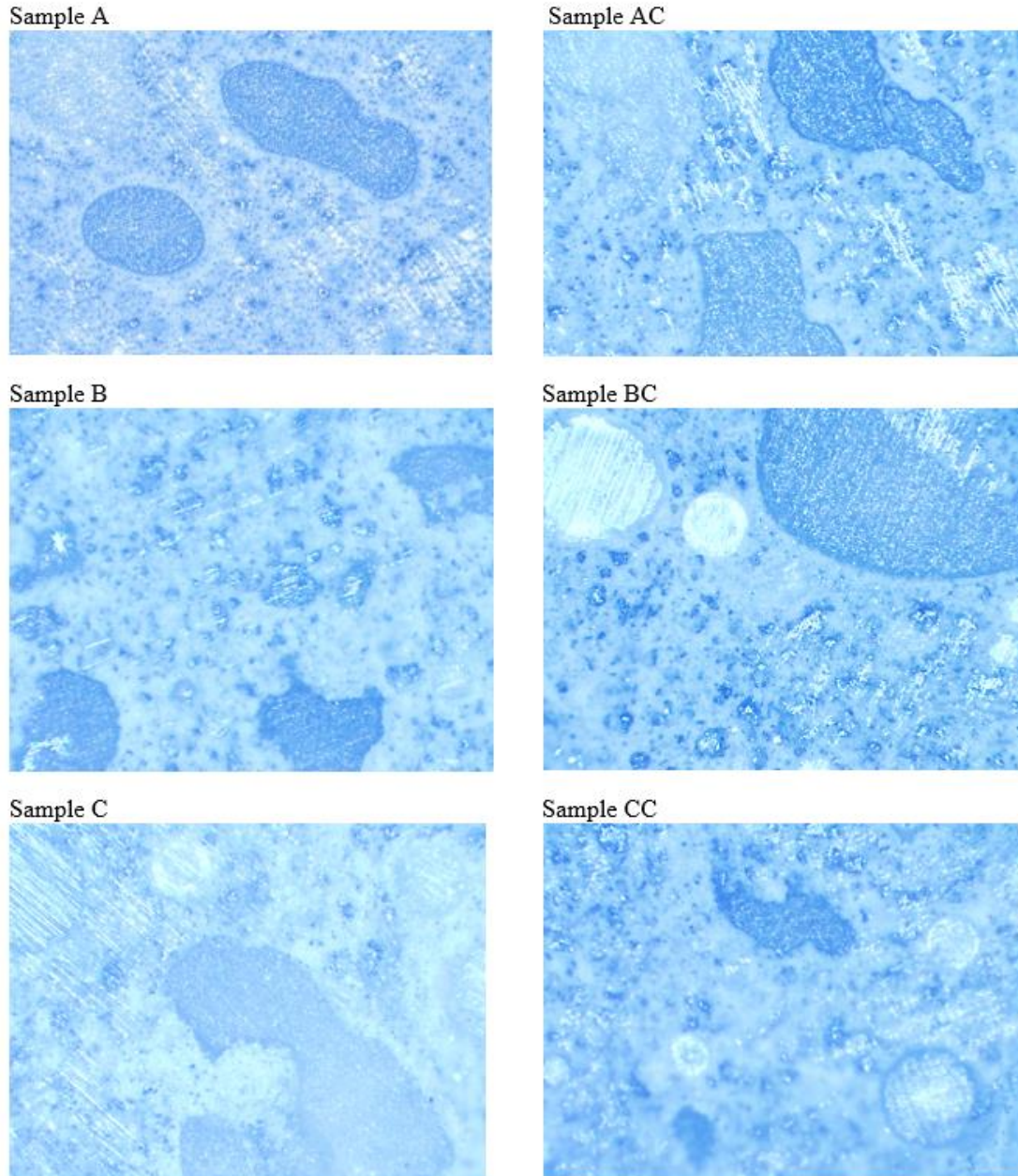


Fig. 19. The samples were observed under a polarizing microscope (Altami Polar 3).

This SEM image of Sample AC as shown in the figure 20 a, exposed to salty water, prominently features needle-like (acicular) crystals characteristic of ettringite formation. These bright, rod-shaped structures (10-50 μm long) emerge from the cement paste matrix, confirming salt crystallization and early sulfate attack, consistent with leaching and surface deterioration. The surrounding heterogeneous paste shows altered regions with increased porosity around aggregates, indicating ion ingress and expansive crystal growth. The image illustrates typical ettringite needles amid the deteriorated paste, validating the described whitening and heterogeneity post-exposure.

For Sample BC as shown in the Fig. 20 b, the SEM image shows a very granular and compact surface, with numerous fine agglomerated particles and only a few larger angular fragments. This indicates a dense, refined paste where glass-powder modification and plastic inclusions have produced a tight microstructure, so salt exposure mainly affects the outermost grains without forming obvious needle-like crystals or visible microcracks, consistent with limited penetration and mild superficial deposition compared with Sample AC.

For Sample CC as shown in the Fig. 20 c, the SEM image shows a refined granular paste surface with uniformly distributed fine particles and only isolated clusters of needle-like salt crystals at the top right. This suggests that the LDPE- and glass-powder-modified matrix develops a denser interfacial transition zone and fewer connected voids, so saline solution mainly causes localized crystal growth rather than widespread leaching or surface disruption, indicating better resistance to salt attack than Sample AC.

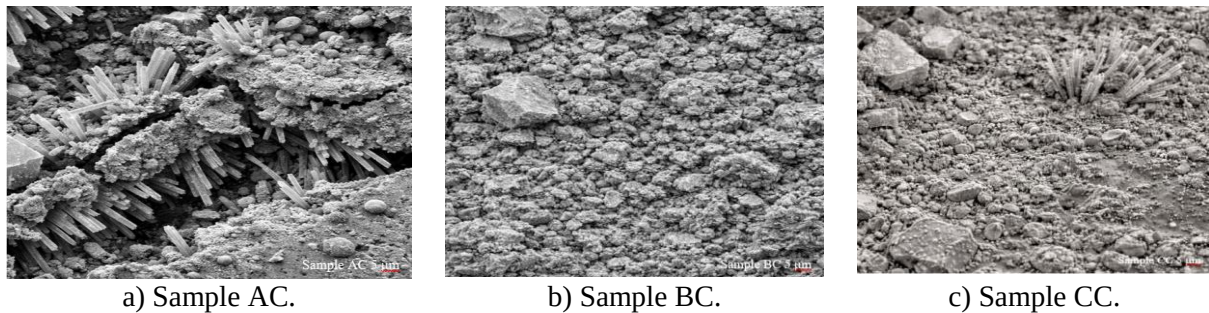


Fig. 20. Samples under QUANTA FEG 250.

As shown in the Fig. 21, Sample A (0% glass, 0% plastic, 45 mm) is the reference normal concrete, where the slump reflects only the selected w/c ratio, cement content and natural aggregates, giving conventional workability. Sample B (10% glass, 5% LDPE, 35 mm) shows a slightly lower but still well-controlled workability, because the limited LDPE replacement together with 10% glass powder gently adjusts the aggregate skeleton and contributes a modest filler effect, resulting in a stable, cohesive mix. Sample C (10% glass, 10% LDPE, 75 mm) exhibits increased workability compared with A, as the finer glass powder improves packing and reduces paste–aggregate friction while the higher proportion of lightweight LDPE particles makes the mix more deformable, allowing it to flow more easily under its own weight. Sample D (10% glass, 15% LDPE, 90 mm) achieves the highest workability, since the aggregate skeleton is more extensively modified by the larger amount of non-absorbent LDPE in combination with the 10% glass filler, which together significantly reduce internal resistance to flow and produce a very fluid mix.

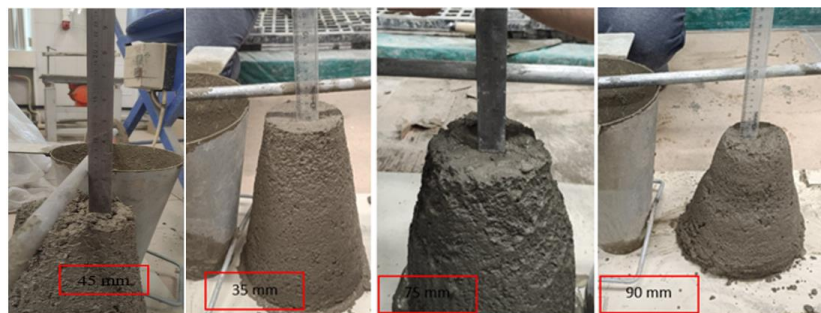


Fig. 21. Slump test for all samples.

The CDP-FEM Studio program was used to calculate the displacement of the concrete sample during the loading process using the FEM model within the finite element analysis framework. The software provided detailed numerical and graphical results that enabled the evaluation of the deformation behavior of the specimen under the applied loads.

The analysis also included a Mesh Load-Step Convergence study, which demonstrated the variation in calculated displacement with different mesh densities and load increments. The results indicated that mesh density significantly influences the accuracy and stability of the finite element model, as finer meshes generally produced more precise displacement predictions and improved convergence behavior. Furthermore, the convergence analysis assisted in determining the optimal mesh size capable of achieving accurate simulation results while maintaining reasonable

computational efficiency and minimizing unnecessary computational time. Figures (22–33) show the displacement results for different concrete samples analyzed using various mesh densities. The results demonstrate the influence of mesh refinement on the predicted displacement behavior of the specimens during the loading process. Different mesh densities were used to evaluate the convergence, accuracy, and stability of the finite element model. The analysis indicated that finer mesh densities generally provided more accurate and consistent displacement predictions, while coarser meshes produced less precise results. These results also helped identify the optimal mesh density that balances simulation accuracy with computational efficiency.

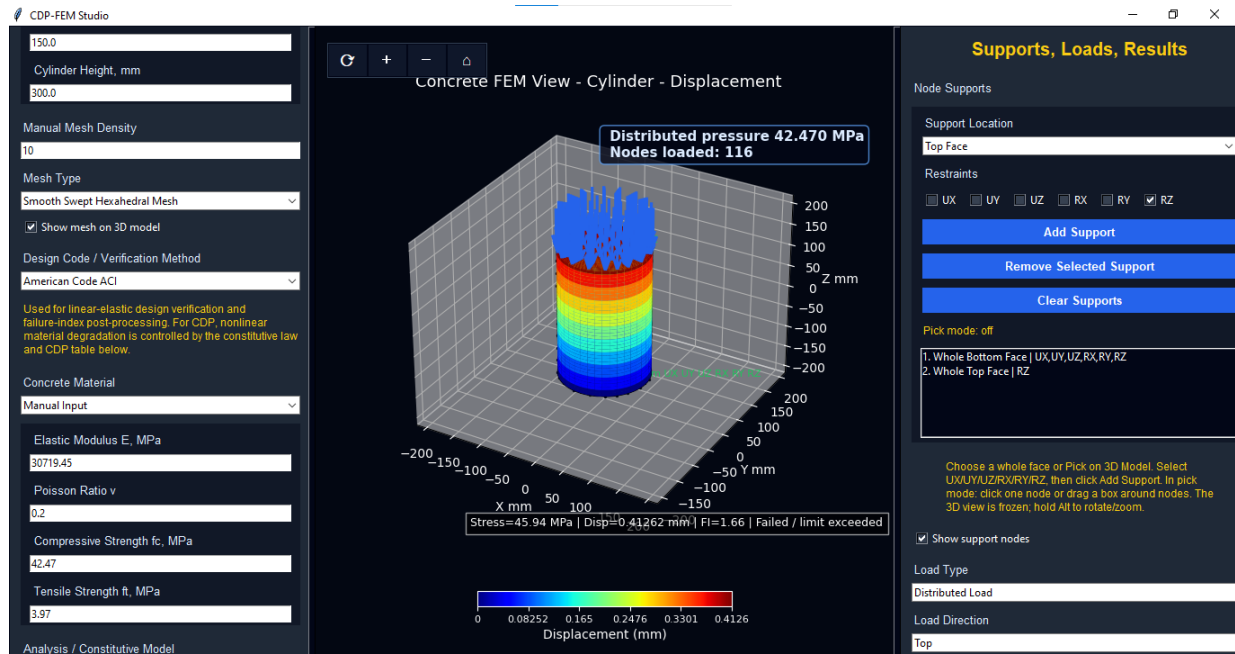


Fig. 22. Interface for CDP-FEM Studio (displacement for sample A).

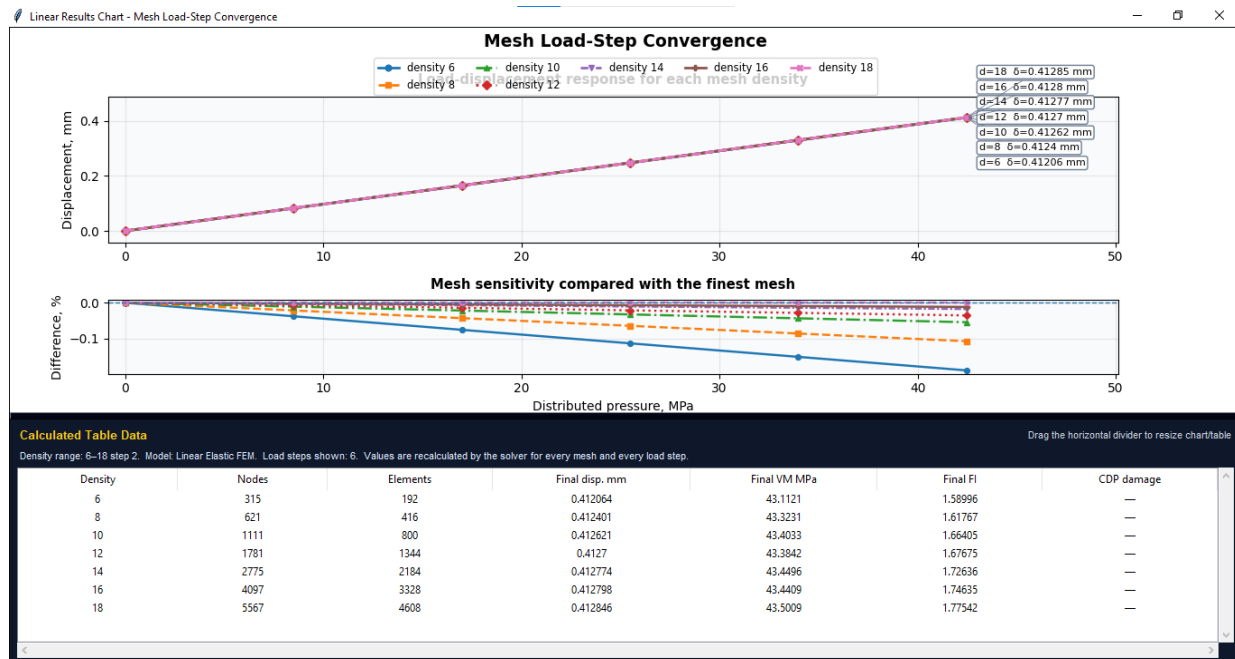


Fig. 23. Mesh Load-Step Convergence (displacement for sample A).

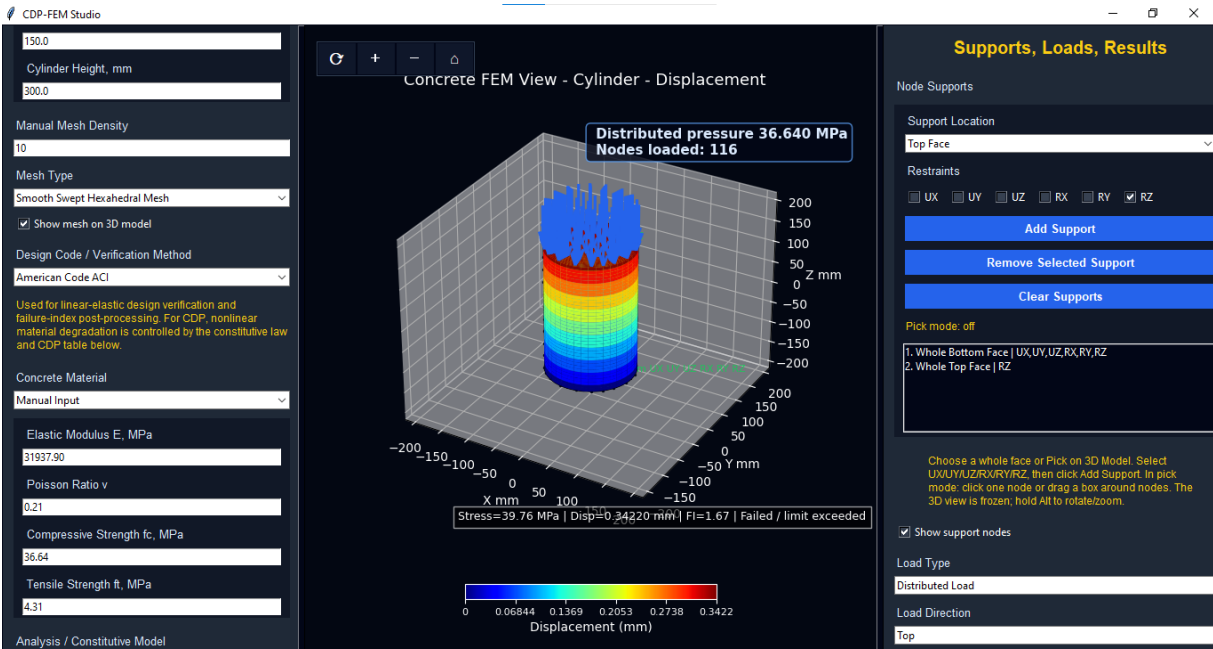


Fig. 24.Interface for CDP-FEM Studio (displacement for sample AC).

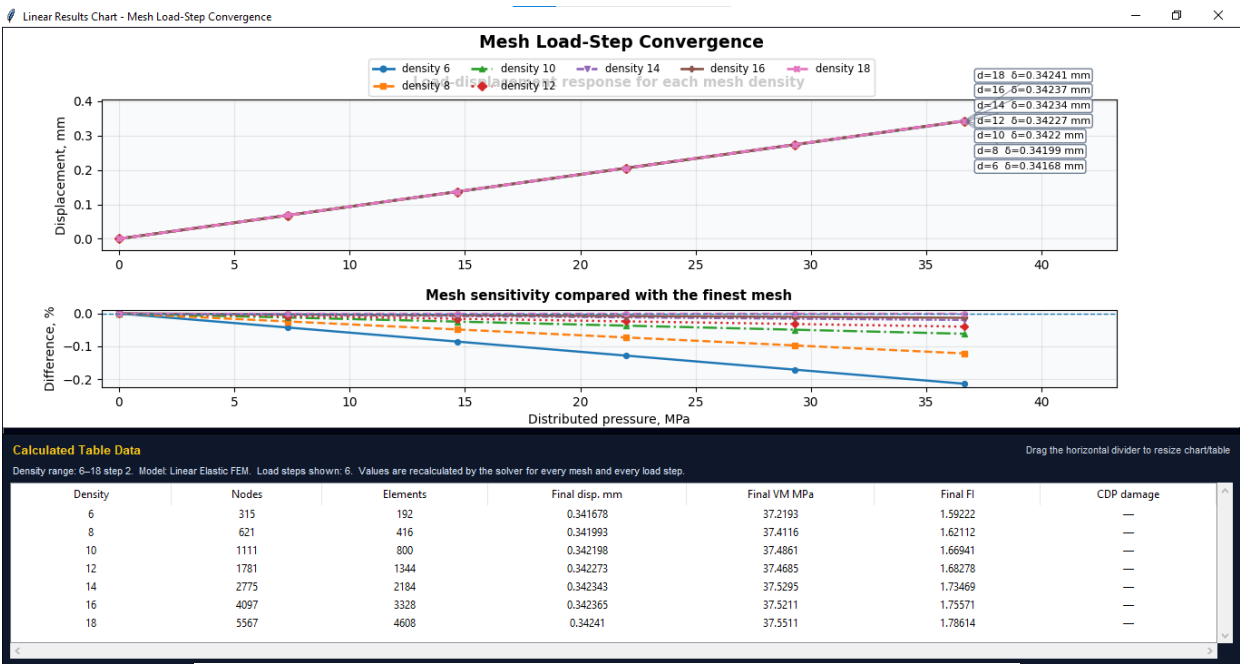


Fig. 25. Mesh Load-Step Convergence (displacement for sample AC).

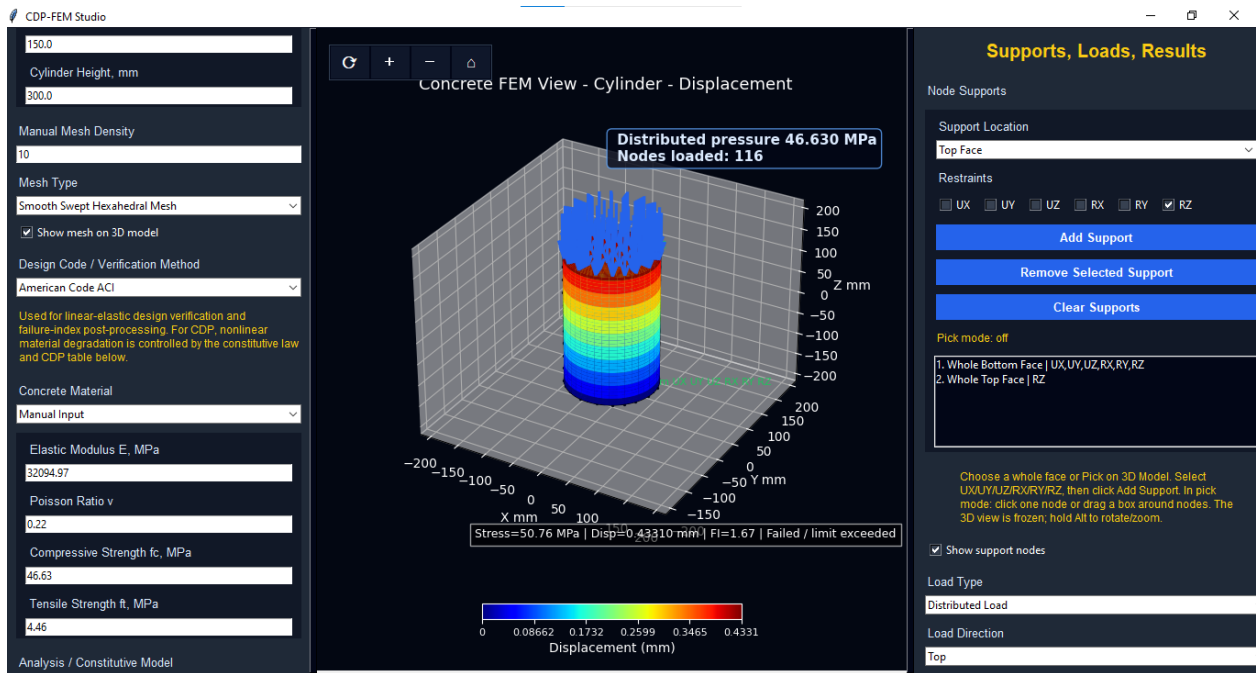


Fig. 26. Interface for CDP-FEM Studio (displacement for sample B).

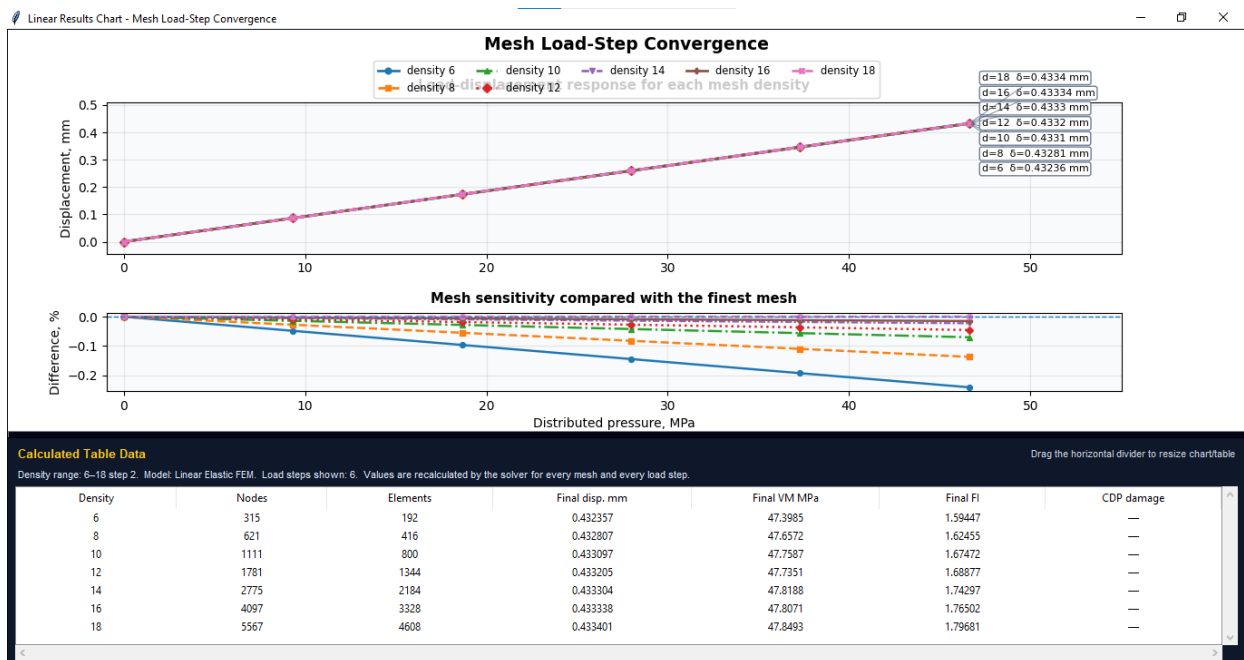


Fig. 27. Mesh Load-Step Convergence (displacement for sample B).

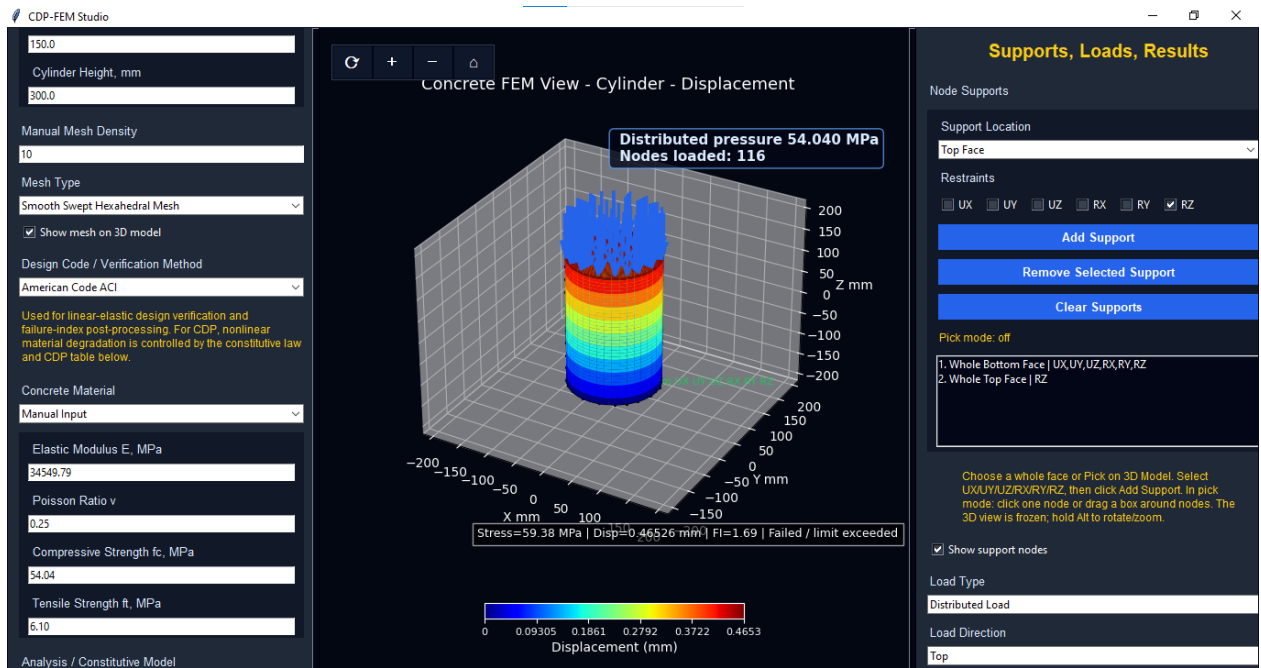


Fig. 28. Interface for CDP-FEM Studio (displacement for sample BC).

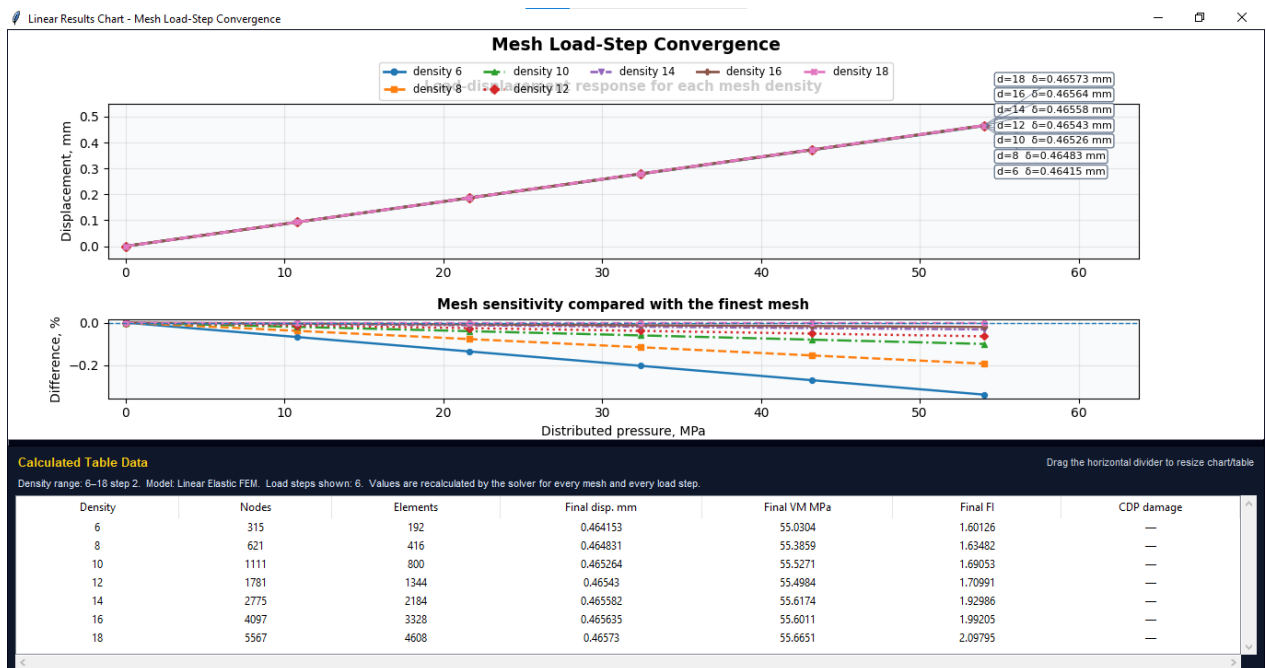


Fig. 29. Mesh Load-Step Convergence (displacement for sample BC).

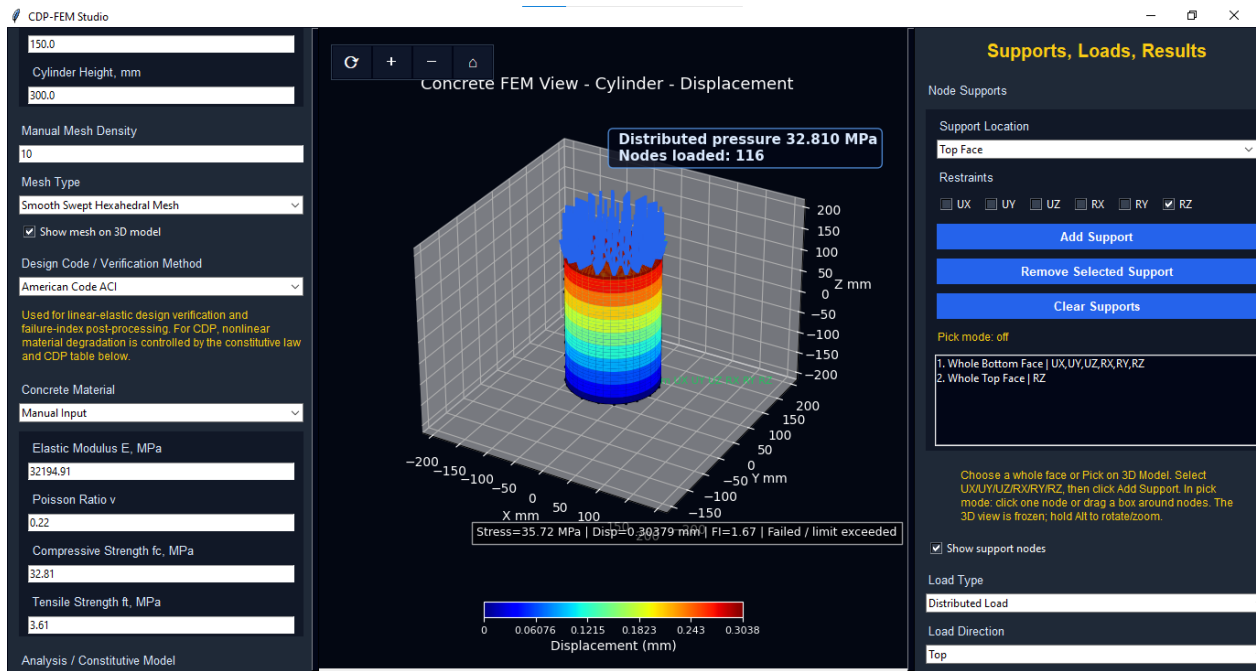


Fig. 30. Interface for CDP-FEM Studio (displacement for sample C).

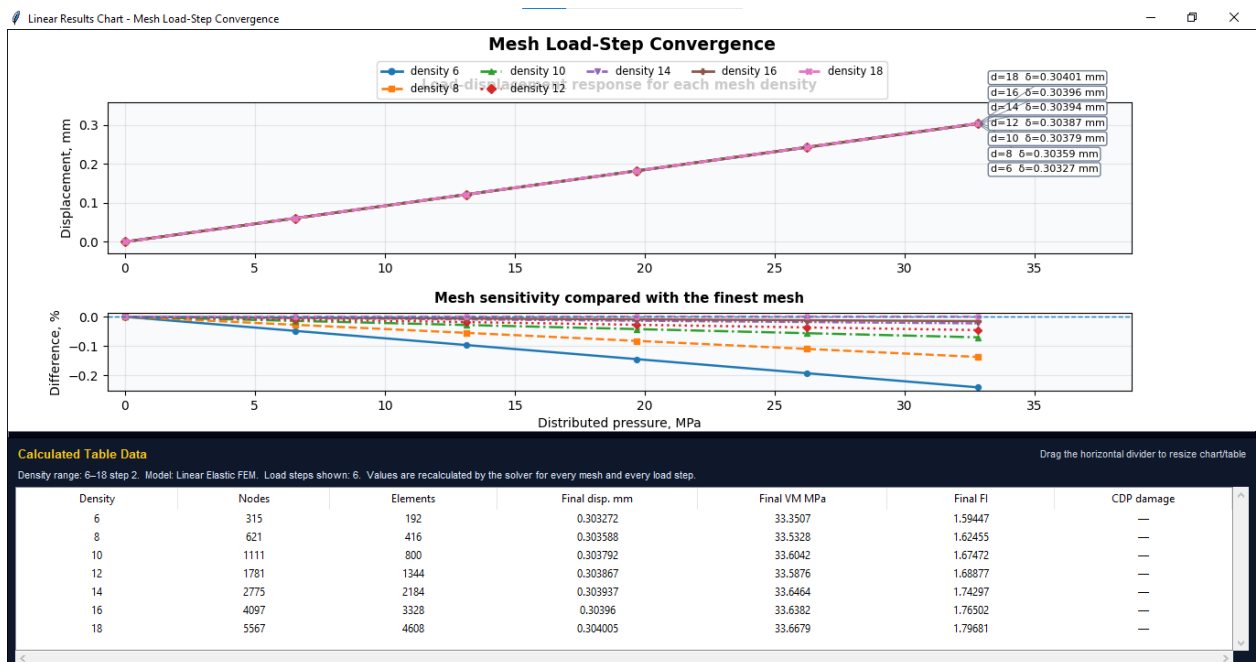


Fig. 31. Mesh Load-Step Convergence (displacement for sample C).

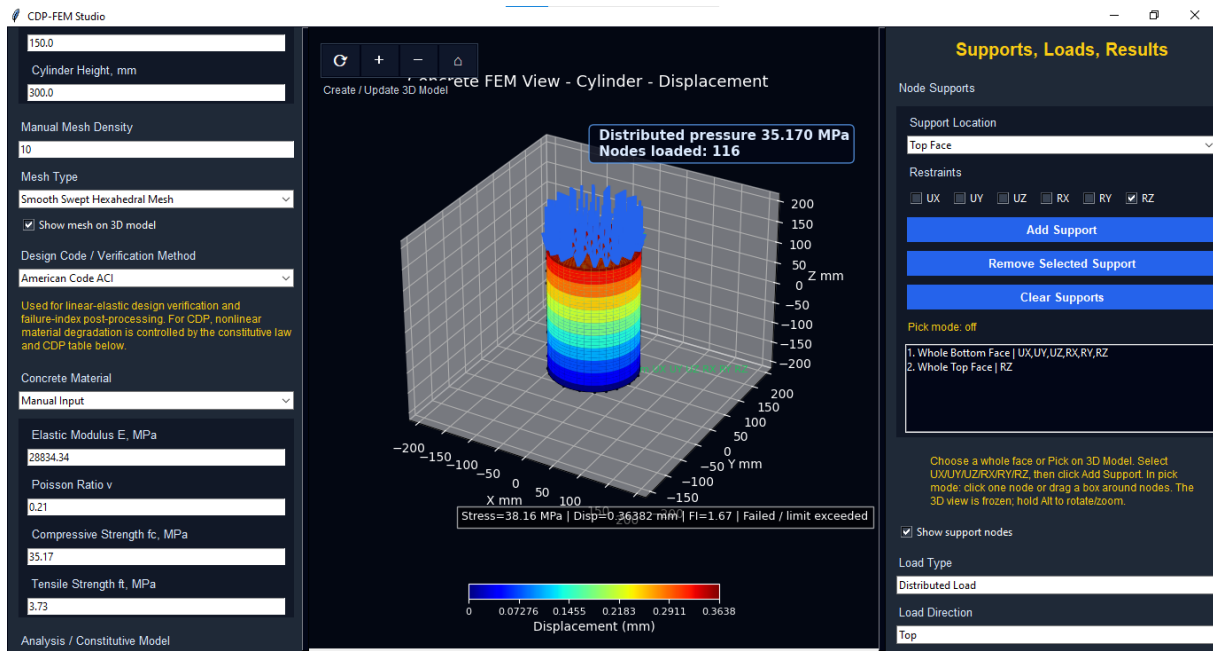


Fig. 32. Interface for CDP-FEM Studio (displacement for sample CC).

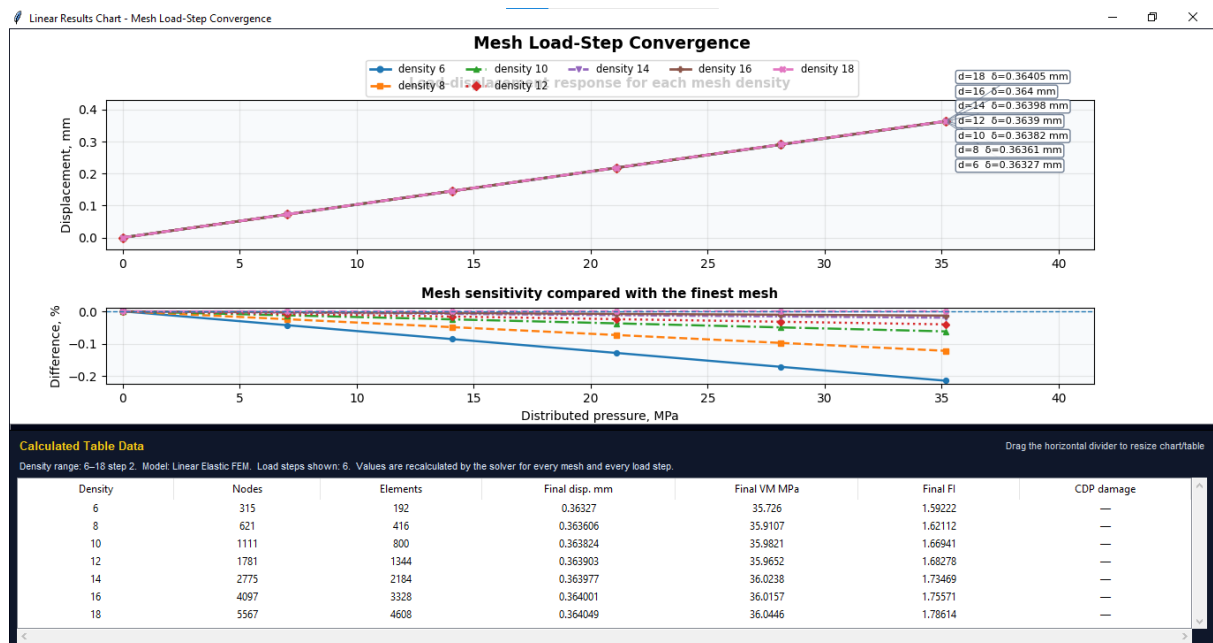


Fig. 33. Mesh Load-Step Convergence (displacement for sample CC).

The comparison between the numerical results obtained from the CDP-FEM Studio program and the experimental results Table 3 demonstrated good agreement in predicting the displacement behavior of the tested concrete samples. The numerical displacement values obtained from the finite element analysis were 0.4126 for sample A, 0.3422 for sample AC, 0.4331 for sample B, 0.4653 for sample BC, 0.3038 for sample C, and 0.3638 for sample CC. The corresponding experimental displacement values were 0.3938, 0.312, 0.350, 0.412, 0.277, and 0.342, respectively.

The results showed that the FEM model provided displacement predictions that were in close agreement with the experimental measurements for all tested samples.

The relatively small differences between the numerical and experimental values demonstrate the accuracy and reliability of the developed finite element model in simulating the deformation behavior of concrete specimens under loading conditions. Furthermore, the consistency between the simulation and experimental results confirms the effectiveness of the CDP-FEM Studio program and validates the adopted mesh convergence and modeling approach used in this study.

Table 3. Comparison Between Numerical and Experimental Displacement Results for Concrete Samples.

Sample	Numerical Displacement (CDP-FEM Studio)	Experimental Displacement	Difference
A	0.4126	0.3938	0.0188
AC	0.3422	0.3120	0.0302
B	0.4331	0.3500	0.0831
BC	0.4653	0.4120	0.0533
C	0.3038	0.2770	0.0268
CC	0.3638	0.3420	0.0218

Abbreviations and definitions:

Sample A: Reference control concrete containing 0% recycled glass and 0% plastic aggregate.

Sample B: Concrete incorporating 10% recycled glass aggregate and 5% plastic waste by volume.

Sample C: Concrete incorporating 10% recycled glass aggregate and 10% plastic waste by volume.

Sample D: Concrete incorporating 10% recycled glass aggregate and 15% plastic waste by volume.

Sample AC: Sample A after exposure to saline water conditions (simulating marine environment degradation).

Sample BC: Sample B after exposure to saline water conditions.

Sample CC: Sample C after exposure to saline water conditions.

4. CONCLUSIONS

Based on the experimental investigation and numerical analysis of concrete incorporating waste glass powder and Low-Density Polyethylene (LDPE) plastic waste, the following conclusions are drawn:

- **Optimal Mix Proportion:** The incorporation of 10% waste glass powder and 5% LDPE granules (Sample B) yielded the optimal mechanical performance, achieving a compressive strength of 46.63 MPa, which represents an enhancement over the control mix (42.47 MPa). Increasing the LDPE content beyond 5% as in samples C and D resulted in a reduction in compressive strength, indicating a threshold for structural viability.
- **Durability in aggressive environments:** Exposure to aggressive saline conditions significantly improved the performance of the modified concrete. Sample BC exhibited a 47.49% increase in compressive strength after 3 months of immersion, whereas the control sample AC declined by 13.72%. This improvement is attributed to the pozzolanic reaction of glass powder densifying the matrix and the hydrophobic nature of LDPE limiting ion ingress.
- **Enhanced Ductility:** The inclusion of LDPE granules improved the tensile strain capacity and ductility of the composite. While the control mix displayed brittle behaviour under tensile stress, the modified samples demonstrated increased deformation capacity before failure, with Sample B offering the most advantageous trade-off between strength and toughness.
- **Microstructural and Simulation Validation:** SEM analysis confirmed that modified mixes BC and CC resisted salt crystallization and ettringite formation better than the control. Furthermore, ABAQUS simulations using the Concrete Damage Plasticity (CDP) model validated these findings, with Sample BC demonstrating the highest Von Mises stress (7.429 and superior stress redistribution capabilities under saline exposure conditions.

- Sustainable Application: The study validates the feasibility of using locally available quartz sand combined with waste glass and plastic for sustainable construction in aggressive environments, such as the Dead Sea region. This approach supports circular economy principles by valorising waste materials while producing concrete with enhanced resistance to chloride penetration and sulphate attack.
- The mesh density convergence analysis was performed using mesh densities ranging from 6 to 18, including 6, 8, 10, 12, 14, 16, and 18. The results showed that the predicted displacement values gradually became more stable and consistent as the mesh density increased. Coarser meshes, particularly at densities of 6 and 8, produced larger variations in displacement results due to lower discretization accuracy. In contrast, finer meshes from 14 to 18 demonstrated improved convergence behavior and more accurate displacement predictions. The analysis indicated that increasing the mesh density enhances the reliability and precision of the finite element model; however, very fine meshes also increase computational time and processing cost. Therefore, the convergence study helped determine an optimal mesh density that provides accurate results while maintaining reasonable computational efficiency.
- The FEM results showed good agreement with the experimental displacement measurements, confirming the accuracy and reliability of the developed finite element model in predicting the deformation behavior of the tested concrete samples.

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