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Comparative Fracture Analysis Of Concrete using LEBM (Linear Elastic Brittle Model)

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Abstract—*This study presents a comparative fracture analysis of concrete using a linear elastic brittle model. Concrete is a widely used construction material and understanding its fracture behavior is crucial for ensuring structural integrity and safety. The linear elastic brittle model offers a simplified representation of concrete's fracture mechanics by assuming linear stress-strain behavior and sudden failure upon reaching the material's ultimate strength. In this research, we investigated the fracture characteristics of concrete specimens under compression loading condition. A series of experiments were conducted to measure the mechanical properties and fracture parameters of the specimens.*
The LEBM was implemented to simulate and predict the fracture behavior of the tested concrete. The comparative analysis involved examining various factors affecting concrete fracture, such as aggregate size, curing conditions. The results revealed significant differences in fracture patterns and ultimate failure loads among the tested specimens. The LEBM accurately captured the observed fracture behavior and provided insights into the governing mechanisms.
Keywords— *LEBM* ***(****linear elastic brittle model), mechanical properties, linear stress-strain behavior*

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I. INTRODUCTION

Nowadays, the awareness about the importance of a sustainable environment is increasing. At the same time rapid urbanization and industrialization has led to the increase in demand for concrete, so as concrete is the fundamental building block for construction, we need deeper understanding of the behavior of concrete as it plays a vital role in development of new concrete types with various characteristic strength, so to develop environment friendly sustainable concrete and forensic structural engineering, fracture mechanics of concrete is a necessary tool.

Fracture refers to the breaking or cracking of a material or structure due to an applied stress or load that exceeds its strength. It is a common type of failure in materials such as metals, ceramics, and composites, as well as in structures such as buildings, bridges, and aircraft components.

Fractures can be classified based on their characteristics, including the mode of fracture (tensile, compressive, or shear), the type of fracture surface (ductile or brittle), and the location of the fracture (surface or subsurface). Some common causes of fractures include overload, fatigue, corrosion, impact, and stress concentrations.

This paper describes a parametric experimental investigation of Fracture analysis of concrete. Fracture analysis is the study of how materials or structures fail under stress or load. It involves examining the fracture surfaces and other features of the failed material or structure to determine the cause of the failure. There are several methods and techniques used in fracture analysis, including visual inspection, microscopy, chemical analysis, mechanical testing, and computer simulation

These results have implications both for future research and for practice, fracture analysis can be used to improve the design of materials and structures, prevent failures, and enhance safety.

II. Fracture Analysis

Fracture analysis of concrete is a branch of material science that deals with understanding the behavior of concrete when subjected to mechanical loads and the consequent fracture patterns. Concrete is a brittle material that undergoes cracking and fracturing when subjected to tensile loads or excessive compression. A

fracture analysis of concrete involves studying the mechanisms of crack propagation, the fracture toughness of the material, and the factors that influence the crack growth and final failure of the structure. The fracture analysis of concrete involves a combination of experimental and theoretical methods.
The following are the steps involved in fracture analysis of concrete:

1. Characterization of material properties: The first step is to determine the mechanical properties of the material, such as the tensile strength, compressive strength, modulus of elasticity, and fracture toughness.
2. Experimental testing: The next step is to subject the material to compressive load and observe the fracture patterns.
3. Fracture mechanics analysis: Fracture mechanics is a theoretical framework that describes the behavior of cracks in materials. It involves calculating the stress intensity factor, which is a measure of the stress at the tip of a crack. By analyzing the stress intensity factor, it is possible to predict the behavior of cracks and the final failure of the structure.
4. Finite element analysis: Finite element analysis (FEA) is a numerical method that can simulate the behavior of materials under different loading conditions. FEA can be used to model the behavior of concrete structures and predict their response to different loading scenarios.

LINEAR ELASTIC BRITTLE MODEL

This model assumes linear elastic behavior for the concrete particles until they reach their ultimate strength. Once the ultimate strength is exceeded, the particles undergo sudden and complete fracture without any post-peak behavior. Particle interactions are typically governed by linear elastic contact laws until failure. The Linear Elastic-Brittle Model is a commonly used theoretical model for fracture analysis of concrete using the Discrete Element Method (DEM). This model assumes linear elastic behavior for the concrete particles until they reach their ultimate strength. Once the ultimate strength is exceeded, the particles undergo sudden and complete fracture without any post-peak behavior. Here are the key characteristics and considerations of the Linear Elastic-Brittle Model.

Elastic Behavior:

Before reaching the ultimate strength, concrete particles behave elastically according to Hooke's law. Stress-strain relationships are linear, and the particles deform reversibly under applied loads. Young’s modulus, Poisson's ratio, and other elastic properties define the particle response.

Ultimate Strength and Fracture:

Once the stress or load on a concrete particle exceeds its ultimate strength, it undergoes sudden and complete fracture. Fracture occurs without any post-peak behavior, and the particle becomes separated into two or more fragments. The model assumes that the fracture process does not involve any energy dissipation or plastic deformation.

Particle Interaction:

Particle interactions are typically governed by linear elastic contact laws until failure. Contact forces between particles are calculated based on the overlapping area and the elastic properties of the particles. When a contact force exceeds the ultimate strength of a particle, it fractures, and the contact is severed.

A. METHODOLOGY.

The DEM Methodology can be broken down into the following steps:

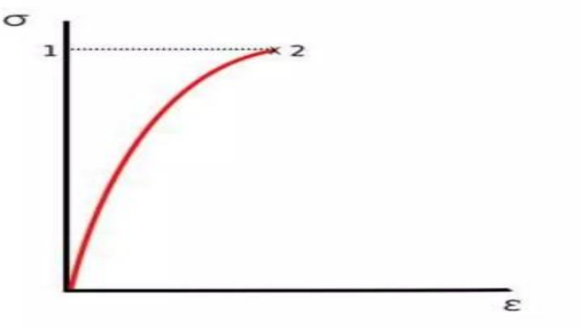
1. **Define the geometry and properties of the particles**: The first step in the DEM algorithm is to define the geometry and properties of the particles. This includes defining the size, shape, density, and surface properties of each particle.
2. **Initialize the simulation**: The second step is to initialize the simulation by placing the particles in a virtual space and assigning initial positions, velocities, and accelerations to each particle.
3. **Calculate the forces between particles**: The next step is to calculate the forces acting between the particles. These forces can be categorized into two types: contact forces and non-contact forces. Contact forces include normal and tangential forces, while non-contact forces include gravitational and electrostatic forces.
4. **Update the particle positions and velocities**: After calculating the forces between particles, the positions and velocities of the particles are updated using numerical integration techniques.
5. **Repeat the simulation**: The simulation is repeated until a desired endpoint is reached, such as a certain number of time steps, a certain deformation or energy level, or until the system reaches a steady state.
6. **Output results**: Finally, the results of the simulation can be outputted and analyzed. This may include visualizing the particle motion, analyzing the stress and strain within the material, or determining the particle flow properties.

B. ANSYS
ANSYS is a computer-aided engineering software suite that is used to simulate and analyze the behavior of various physical systems, including structures, fluids, electromagnetics, and electronics. It is a popular tool among engineers, scientists, and researchers in many different industries.
ANSYS provides a wide range of capabilities, including finite element analysis (FEA), Discrete Element Method (DEM), computational fluid dynamics (CFD), and electromagnetic field simulation. It can be used for both static and dynamic analyses, as well as for Multiphysics simulations that involve the interaction of multiple physical phenomena.

III. ANALYSIS

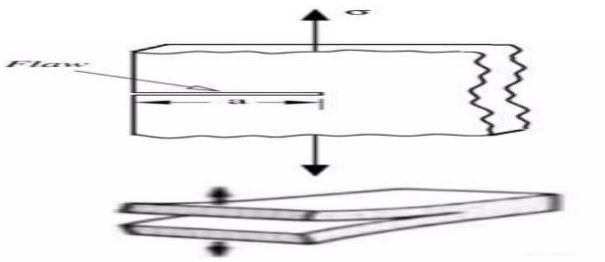
A. Brittle Fracture
Brittle fracture takes place without any appreciable deformation, and by rapid crack propagation. The direction of crack motion is very nearly perpendicular to the direction of applied tensile stress and yields a relatively flat fracture surface.

B. Factors affecting fracture
1. Stress Concentration
2. The speed with which the load is applied
3. The temperature
4. Thermal shock loading



Stress v/s strain graph

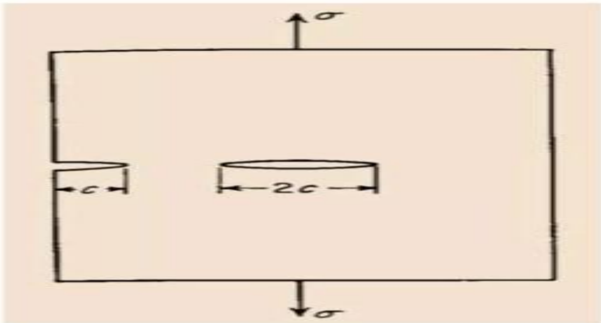
C. Fracture toughness
Defects and cracks are present in all engineering materials. They may be introduced during solidification or heat treatment stages of the material. The fracture resisting capacity of machine component or engineering structures must be evaluated in the presence of cracks. The fracture resistance of a material in the presence of a crack or discontinuities is known as its fracture toughness.
The fracture toughness is defined by the critical value of parameter ‘Gc’. ‘Gc’ gives the value of the strain energy release per unit area of the crack surface when unstable crack extension take place. For an elastic crack of length ‘2c’,
Brittle material contains a population of fine small cracks and flaws that have a variety of sizes , geometries and orientation which produces a stress concentration of sufficient magnitude so that the theoretical cohesive strength is reached in localized regions at a nominal stress which is well below the theoretical value.
When one of the cracks spreads, it produces an increase in the surface area of the side of the crack. This requires energy to overcome the cohesive force of the atom Or express in another way, It requires an increase in surface energy. The source of increased in surface energy is the elastic strain energy which is released as the crack spreads.



Crack propagation.

A crack will propagate when the decrease in elastic strain energy is at least equal to create the new Crack." the decrease in strain energy results from the formation of a crack. Consider the crack model as shown in figure. The thickness of the plate is negligible so the problem can be treated as one in plane stress. The cracks are assumed to have an elliptical shape.
Crack length = interior = 2c = edge = c The effect of both types of cracks on the fracture behavior is the same

Grade of concrete	M25
Dimension of cube	150mmX150mmX150mm
Cross sectional area	22500mm2
Test method	IS : 516
Strength	16.25 N/mm2



Crack propagation theory

The crack will propagate under a constant applied stress σ if an incremental increase in crack length produces no change in the total energy of the system; i.e. the increased surface energy is compensated by a decrease in elastic strain energy.
Using principles of fracture mechanics, it is possible to show that the critical stress σ_c required for crack propagation in a brittle material is described by the expression

$$\sigma_c = \left(\frac{2E\gamma_s}{\pi a}\right)^{1/2}$$

Where, E= modulus of elasticity
γ_s = specific surface energy
a= one half the length of an internal crack

all brittle materials contain a population of small cracks and flaws that have a variety of sizes, geometries, and orientations. When the magnitude of a tensile stress at the tip of one of these flaws exceeds the value of this critical stress, a crack form.

D. LAB TEST RESULTS OF CONCRETE CUBES

Table I. M-25 OPC Concrete Mix Design

Mix Proportions for One Cum of Concrete (SSD Condition)	
Mass of Cement in kg/m3	**320**
Mass of Water in kg/m3	**138**
Mass of Fine Aggregate in kg/m3	**751**
Mass of Coarse Aggregate in kg/m3	1356
Mass of 20 mm in kg/m3	**977**
Mass of 10 mm in kg/m3	**380**
Mass of Admixture in kg/m3	**1.60**
Water Cement Ratio	0.43

required (min)	

Compression test results

SL no.	Age at test (Days)	Maximum Load (kN)	Compressive strength (N/mm2)	Average Strength (N/mm2)
1	7	528	23.470	
2	7	622	27.640	26.42
3	7	633	28.140	
4	28	799	35.510	
5	28	853	37.910	38.00
6	28	913	40.580	

TABLE II. M30 GGBS concrete mix design

Mix Proportions for One	**Cum of Concrete (SSDCondition)**
Grade	M30
W/CRatio	0.37
Cement(Kg/Cu.m)	190
GGBS(Kg/cum)	190
GGBS(kg/Cum)	50%
20 mm(Kg/Cu.m)	671
10 mm(Kg/Cu.m)	459
crushedstonedust(kg/cum)	576
slagSand(Kg/Cu.m)	187
Water(Kg/Cu.m)	140
Admix.(Kg/Cu.m)	1.48
Total Wt.(Kg/ Cu.m)	2414
Design Slump	75-125
Slump Observed	120

Grade of concrete	M30
Dimension of cube	150mm X 150mm X 150mm
Cross sectional area	22500mm2
Test method	IS : 516
Strength required (min)	42 N/mm2

Compression test results

SL no.	Age at test (Days)	Maximum Load (kN)	Compressive strength (N/mm2)	Average Strength (N/mm2)
1	7	828	36.78	
2	7	869	38.64	39.11
3	7	943	41.91	
4	28	1119	49.74	
5	28	1166	51.81	51.80
6	28	1212	53.86	

TABLE III. Geopolymer concrete mix design

Sample	Molarity (M)	Binder to aggregate ratio	Fly ash (g)	Fine aggregate (g)	Coarse aggregate (g)	Sodium hydroxide solution (g)	Sodium silicate solution (g)
S1	10	40:60	640	576	864	91.4	228.6
S2	10	35:65	560	624	936	80.0	200.0
S3	10	30:70	480	672	1008	68.6	171.4

Chemical composition of fly ash

Elements	Al2O3	SiO2	Fe2O3	CaO	SO3	K2O	TiO2	MnO	NiO	CuO
Mass percentage (%)	17.5	39.6	18.1	16.6	3.03	2.13	1.30	0.13	0.02	0.06

Dimension of cube	150mm X 150mm X 150mm
Cross sectional area	22500mm2
Test method	IS : 516

Compression test results

SL no.	Age at test (Days)	Maximum Load (kN)	Compressive strength (N/mm2)	Average Strength (N/mm2)
1	7	796	35.38	
2	7	848	37.69	38
3	7	921	40.93	
4	28	1189	52.84	
5	28	1254	55.73	56
6	28	1339	59.51	

Slump Test of concrete

Filled concrete cube mould

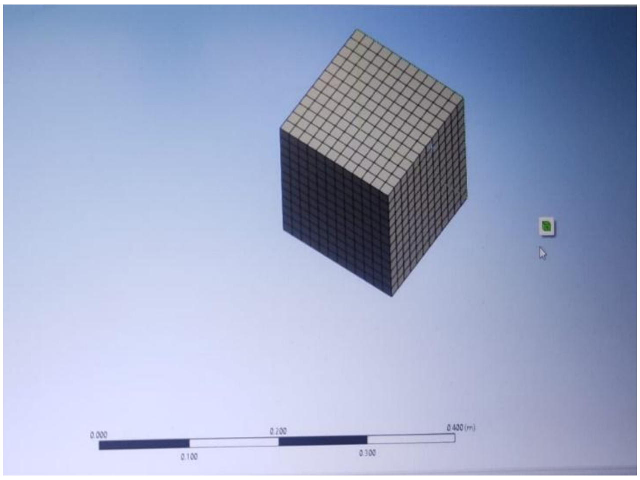
Test specimens

Test specimen failure

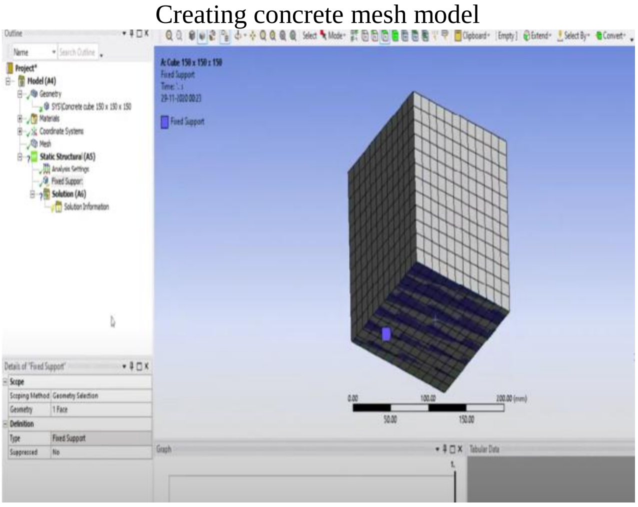
E. ADVANTAGES AND APPLICABILITY

a. The Linear Elastic-Brittle Model is relatively simple and computationally efficient compared to more complex fracture models.
b. It can provide quick insights into the fracture behavior of concrete under various loading conditions.
c. This model is suitable for initial screening studies, where detailed post-peak behavior is not the primary focus.
d. While the Linear Elastic-Brittle Model offers simplicity and efficiency, it is important to consider its limitations when applying it for fracture analysis.
e. Depending on the specific objectives and requirements of the analysis, more sophisticated fracture models, such as damage mechanics or cohesive zone models, may be necessary to capture the realistic behavior of concrete in the post-failure regime.

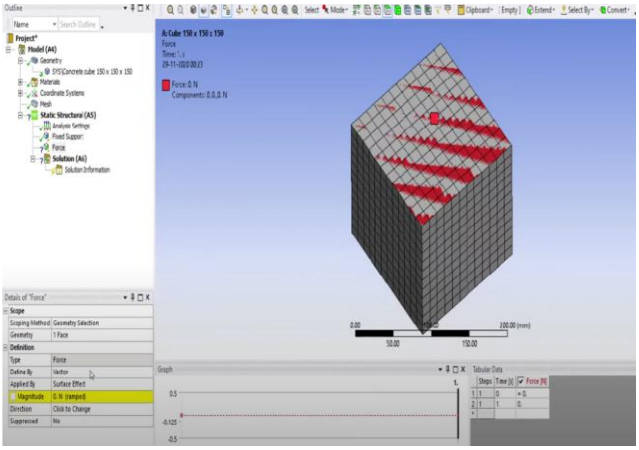
F. SOFTWARE ANALYSIS



Creating concrete mesh model



Applying Support for cube

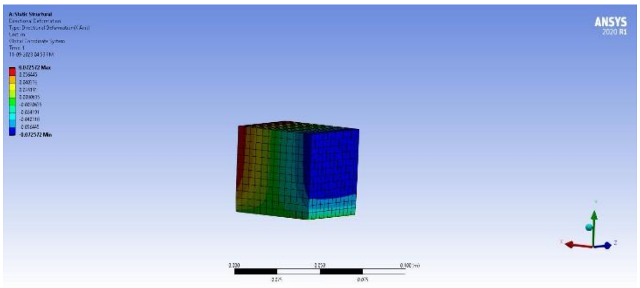


Applying load on specimen

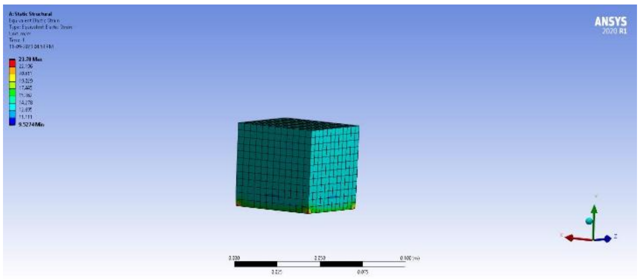
IV. RESULTS AND DISCUSSION

The Ansys software simulation results of all types of concrete cubes under compression tests are as follows as per von mises failure criterion.

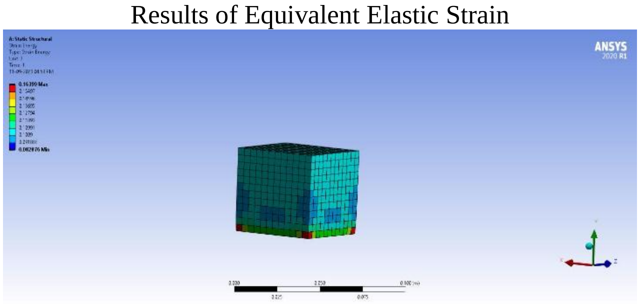
For M25 concrete cube with Ordinary Portland Cement compression test results after curing for 7 days



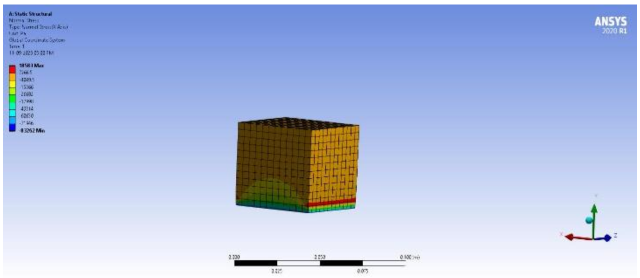
Results of Directional Deformation



Results of Equivalent Elastic Strain

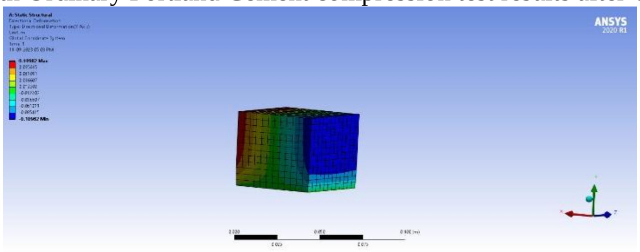


Results of Strain Energy

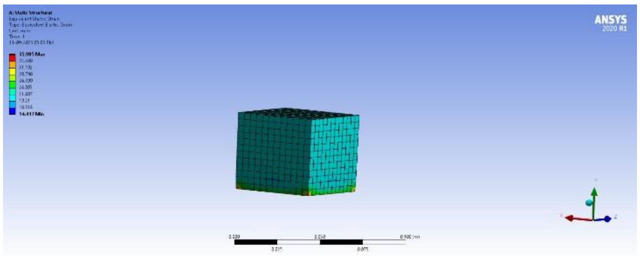


Results of Normal Stress

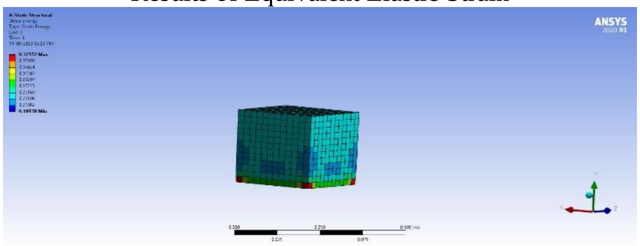
For M25 concrete cube with Ordinary Portland Cement compression test results after curing for 28 days.



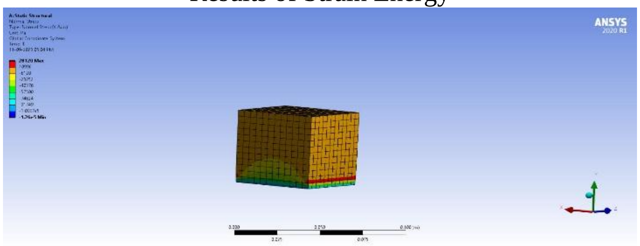
Results of Directional Deformation



Results of Equivalent Elastic Strain

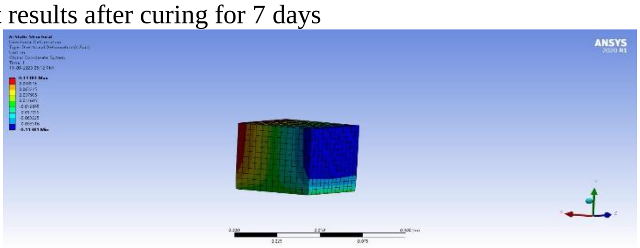


Results of Strain Energy

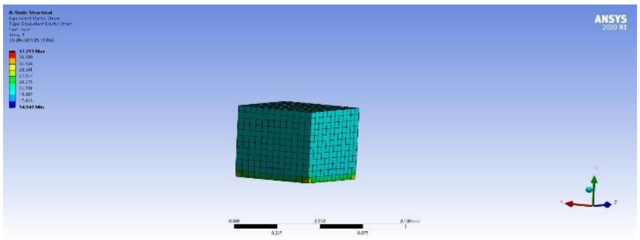


Results of Normal Stress

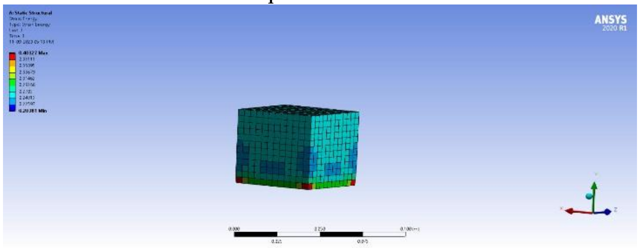
For M30 concrete cube with 50% replacement of OPC with GGBS and 24% replacement of fine aggregates with slag sand compression test results after curing for 7 days



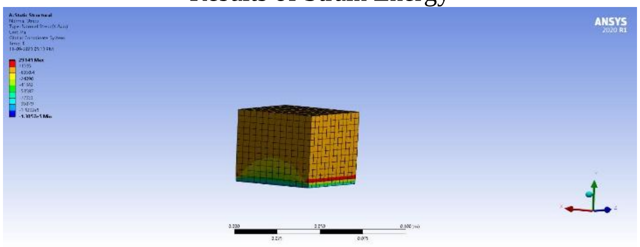
Results of Directional Deformation



Results of Equivalent Elastic Strain

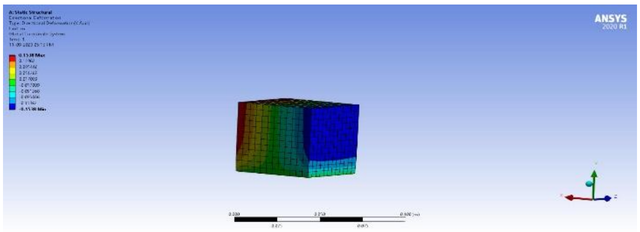


Results of Strain Energy

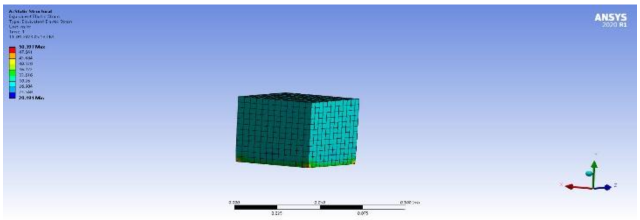


Results of Normal Stress

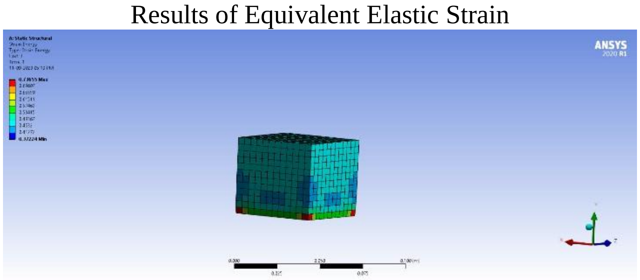
For M30 concrete cube with 50% replacement of OPC with GGBS and 24% replacement of fine aggregates with slag sand compression test results after curing for 28 days



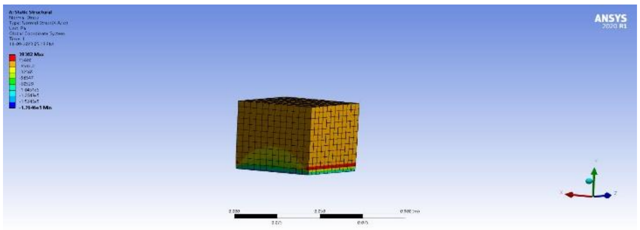
Results of Directional Deformation



Results of Equivalent Elastic Strain

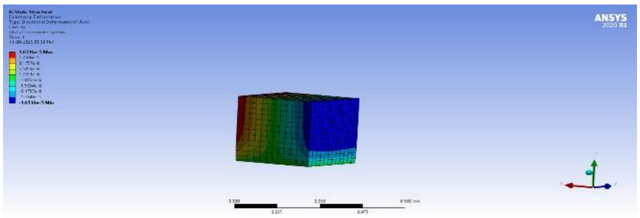


Results of Strain Energy

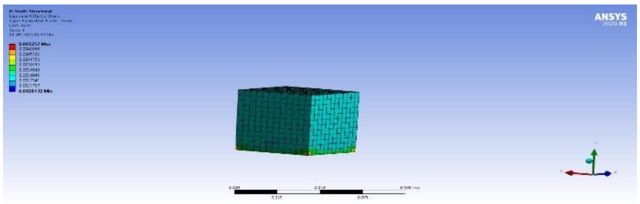


Results of Normal Stress

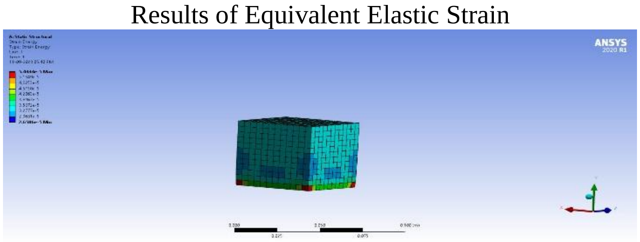
For Geopolymer concrete cube with 10M molarity NaOH solution compression test results after curing for 7 days



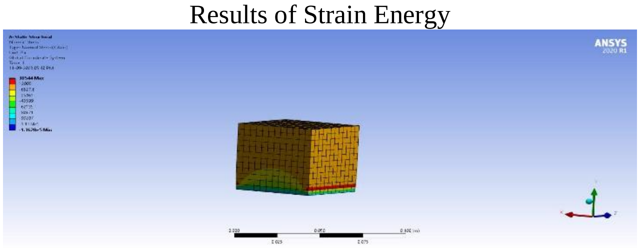
Results of Directional Deformation



Results of Equivalent Elastic Strain

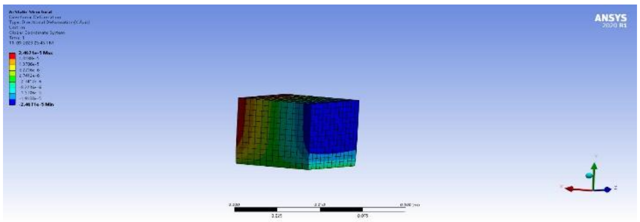


Results of Strain Energy

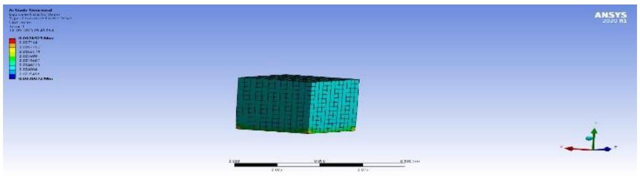


Results of Normal Stress

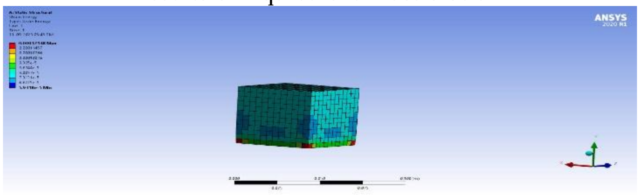
For Geopolymer concrete cube with 10M molarity NaOH solution compression test results after curing for 28 days



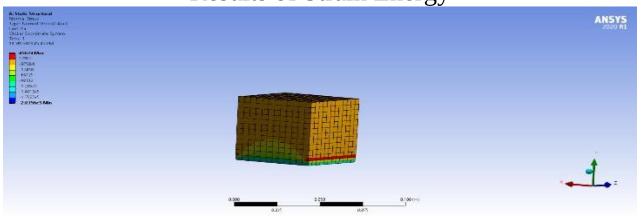
Results of Directional Deformation



Results of Equivalent Elastic Strain



Results of Strain Energy



Results of Normal Stress

Overall the results look promising with minimum variation between Theoretical, Software simulation and experimental and this proves that LEBM method can be used to study the behavior of concrete in linear elastic phase.

As LEBM is simple method to determine failure behavior of concrete this can be used for investigation purposes.

V. CONCLUSION

The comparative fracture analysis of concrete using the Linear Elastic Brittle Model (LEBM) is a crucial project that provides valuable insights into the behavior of concrete under various loading conditions. In this report, we have explored and analyzed the fracture properties of concrete specimens using the LEBM, and we have reached several significant conclusions

a. Material Characterization: The project has successfully demonstrated the importance of accurately characterizing the material properties of concrete, such as Young's modulus and fracture toughness. These parameters are essential for applying the LEBM and predicting crack propagation accurately.

b. Crack Propagation Patterns**:** Through the use of the LEBM, we have observed that concrete typically exhibits linear elastic behavior up to a critical stress level, beyond which it experiences rapid crack propagation. This critical stress level is an important parameter to consider in designing structures to prevent catastrophic failure.

c. Limitations of LEBM: While the LEBM is a valuable tool for fracture analysis, it has limitations, particularly in capturing the full complexity of concrete behavior under all circumstances. It assumes linearity and brittleness, which may not always accurately represent concrete's behavior in certain situations, such as dynamic loading or high-stress conditions.

VI. FUTURE SCOPE

This project opens avenues for future research into advanced modeling techniques that can better capture the nonlinear behavior of concrete, especially in post-cracking phases. Additionally, further investigations can explore the influence of different additives and mix designs on concrete's fracture properties.

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