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Finite Element Analysis of Axial Compression Behaviour of Recycled Aggregate Column using ABAQUS

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Abstract - *Concrete is the most commonly used construction material, which has been used in all types of Civil Engineering construction works. For a sustainable environment and to alleviate the problems of the large annual production of construction and demolition waste, the recycled aggregate concrete has been incorporated in the concrete. Presently, the numerical models for the axial compression load assessment on columns are starting to become more accurate and reliable. In the present research, the ABAQUS program is used to model the behaviour of reinforced concrete (RC) short columns subjected to axial loading. The Nonlinear finite element model uses the concrete damaged plasticity (CDP) approach. The model used in the present study can help to compare the experimental investigations under considerations as a valuable data for the design aspect. Four columns of size 150X150X1200mm with four different mixes with partial replacement of Natural coarse aggregate with Recycled coarse aggregate (RCA) and Treated recycled coarse aggregate (TRCA) are modelled in ABAQUS 6.14 and tested for axial compressive strength to observe the parameters such as first crack load, ultimate load and stress-strain behaviour, then the analytical results are compared with experimental results. Hence, the Nonlinear finite element models can simulate the behavior of recycled aggregate columns under axial compression load and there was good agreement of analytical results obtained from ABAQUS 6.14 with that of experimental results.*

Key Words: *ABAQUS, Nonlinear Finite element analysis, Stress Strain Behaviour, Concrete Damage Plasticity, Recycled Coarse Aggregate, Treated Recycled Coarse Aggregate*

1. INTRODUCTION

With rapid urbanization, one of the fastest growing industries is construction and it is expected to continue growing exponentially with the increase in urban population. In order to decrease the construction waste, recycling of waste concrete as aggregate is beneficial and effective for preservation of natural resources at the same time minimizing the disposal problems. The use of recycled coarse aggregates (RCA) in structural concrete reduces the aggregates transportation distances, CO_2 emissions, and landfill space required for the construction waste material by enhancing the protection of the natural environment in a sustainable way.

The Finite Element Analysis (FEA) is the simulation of any given physical phenomenon using the numerical technique called Finite Element Method (FEM). Engineers use FEA software to reduce the number of physical prototypes and experiments and optimize components in their design phase to develop better products, faster while saving on expenses. The use of FEA tools has become widespread due to increased computation power and the ability of FEA software packages to simulate incredibly complicated components, structures and systems under a wide variety of situations and loading conditions.

Very few analytical investigations have been conducted under axial compression loading for concrete columns that contain combination of untreated and treated recycled coarse aggregates. So, in this study a Finite element analysis is carried out using ABAQUS 6.14.

2. LITERATURE REVIEW

The present analytical analysis is concentrated on axial compression behaviour of short columns using RCA and treated RCA as partial replacement for NCA concrete. Numerous researches focused their studies on Recycled aggregate concrete and analytical investigation using Finite element method of Reinforced Concrete components.

The Properties of recycled concrete aggregate under different curing conditions (air, water, paint) and increasing the concrete age led to an increase in its compressive strength. According to the best ratio of recycled aggregates to natural aggregates is the mixing ratio of 50% and that when they are cured in air or painted, the maximum value of the compressive strength and tensile strength was obtained at age of 28 days. [2,3] Conducted an experimental study on recycled aggregate concrete obtained from the construction demolition waste and used it as a full replacement for natural coarse aggregate with mix ratio 1:2:4 and w/c of 0.5, and carried out compressive strength test at 7,14,21, 28 days. The 28 days compressive strength of 12 batches of recycled aggregate concrete which they have obtained is 29.42 N/mm^2 which were greater than characteristic compressive strength of 25 N/mm^2. The experimental and the theoretical studies about the elasticity modulus and energy capacities [4]. Fifteen concrete mixtures are produced with different ratios of replacement of natural coarse aggregate with recycled coarse aggregate, and at the age of 28 days, the tests (compressive strength, modulus of elasticity in compression, splitting tensile strength and density) are applied on the specimens (150mm diameter and 300mm length cylinder).

A computational model for studying the mechanical performance of steel-concrete columns under combined torsion is established via ABAQUS [5]. Through numerical simulations, the influence of the axial load ratio, torsion-bending ratio, concrete strength, steel ratio, longitudinal reinforcement ratio, stirrup ratio, and shear-span ratio on the torsional behaviour of steel-concrete columns is comprehensively was investigated. [6] used the ABAQUS program to model the behaviour of reinforced concrete (RC) beams. The size of beam used was 305 X 770 X 6095mm and was modelled in ABAQUS using model proposed by Saenz [13]. The results indicated that the displacement, tensile strain for the main reinforcement, compressive strain for concrete and crack patterns obtained from the finite element model (FEM) are well matched with the experimental results. A 3D model of a concrete cube was prepared using smeared crack model and concrete damage plasticity approach by [7]. A comparative study for cube of size 150mm modelled in ABAQUS using C3D8 element was done using different models and their results were discussed. [8] presented a finite element analysis of eight identical beams of size 150 X 300 X 1960mm for the effect of retrofitting with Carbon fiber reinforced polymer. A nonlinear finite element analysis was carried out using stress strain relationship proposed by Saenz[13]. The analyses results showed good agreement with the experimental data regarding load–displacement response, crack pattern and debonding failure mode when the cohesive bond model was used. The perfect bond model failed to capture the softening behaviour of the beams. There is no significant difference between the elastic isotropic and orthotropic models for the CFRP. [9] has used recycled aggregate concrete (RAC) in the columns reinforced with glass fiber reinforced polymer (GFRP) bars. This study compared the structural behavior of GFRP reinforced recycled aggregate concrete columns (GRAC columns) and steel bars reinforced recycled aggregate concrete columns (SRAC columns) under concentric and eccentric loadings. The close agreements were observed among the experimental results, numerical simulations, and theoretical predictions for test specimens. [10] presented a simple but robust finite-element (FE) model for simulating the bond behavior in the entire debonding process for the single shear test. A concrete damage plasticity model was proposed to capture the concrete-to-FRP bond behavior. Numerical results were in close agreement with test data, validating the model. A nonlinear finite element analysis (NLFEA) is conducted by [11] in ABAQUS/STANDARD software to analyse the reinforced concrete short column and the finite element analysis results was compared to experimental results. Stress strain relationship for concrete under uniaxial compression and tension proposed by Saenz[13] was used for modelling of the columns. [12] proposed a numerical finite element model, including a reliable finite element modeling technique and constitutive material models, to simulate nonlinear behavior of reinforced concrete deep beams. Numerical results were compared with experimental results in terms of load-displacement and damage distribution behaviors. Analysis was performed by using a commercial FE program ABAQUS. The analysis results were demonstrated that finite element analysis is a highly effective and reliable tool to simulate nonlinear behavior of reinforced concrete deep beams. From the detailed literature review, it has been concluded that columns casted using RCA as partial replacement have shown the similar results with that of Conventional concrete column.

Hence an attempt has been made in the present study to validate existing Finite element model with [8] in ABAQUS 6.14 and the same concrete damaged plasticity model is used to compare the experimental results obtained.

3. EXPERIMENTAL WORK

As from the experimental results obtained for reinforced aggregate concrete was prepared by partial replacement of crushed concrete coarse aggregates with natural coarse aggregates. The study also includes treating the recycled concrete aggregates with Nitoflor Lithurin (basically mixture of sodium silicate and lithium silicate solutions) to enhance the surface properties of RCA.

Twelve identical columns of size 150X150X1200mm as shown in Figure 1 with four different mixes (i) C-1:100%NCA(conventional concrete of grade M-25) (ii) C-2:50%TRCA+50%NCA (M-25 grade concrete made using 50% treated recycled concrete aggregate and 50% natural coarse aggregate)(iii) C3:50%TRCA+30%NCA+20%RCA,(M-25grade concrete made using 50% treated recycled concrete aggregate, 30% natural coarse aggregate and 20% recycled concrete aggregate) and(iv) C-4: 80%NCA+20%RCA (M-25 grade concrete made 80% natural coarse aggregate and 20% recycled concrete aggregate) were casted and tested for axial compression behaviour at Department of Civil Engineering, UVCE, Bangalore University, Bengaluru, and Karnataka, India.

Stress-strain curve for all the four columns is presented in the Figure 2. The results like First crack load and ultimate load are determined and also the theoretical and experimental load, strains and young's modulus were compared.

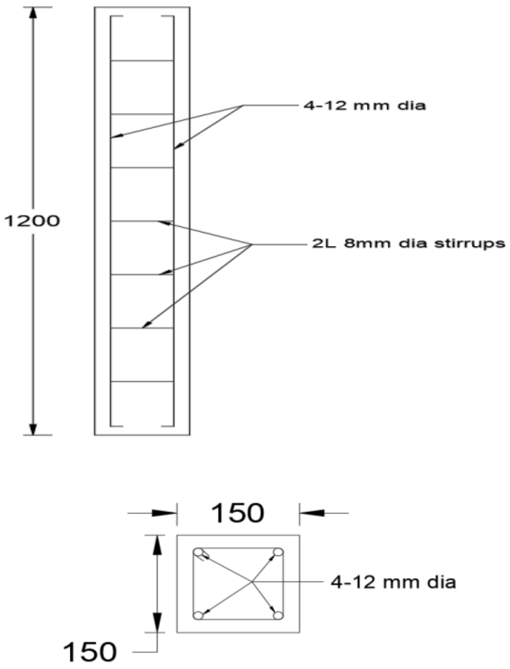


Fig -1: Geometry, reinforcement of the tested columns

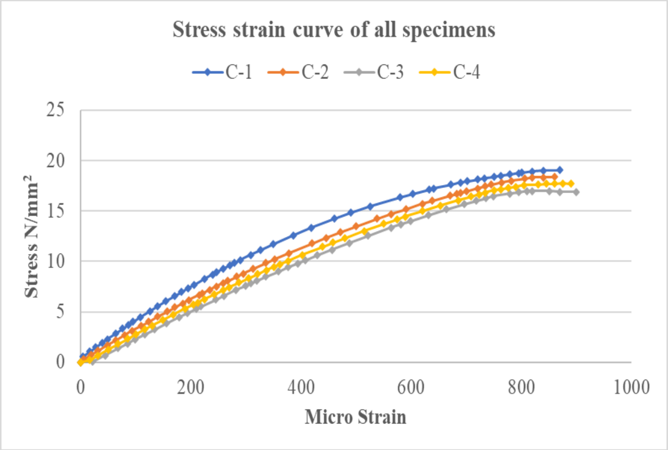


Fig -2: Experimental Stress strain curve of all specimens

4. FINITE ELEMENT ANALYSIS

Finite element analysis was performed to model the nonlinear behaviour of the recycled aggregate columns of size 150X150X1200mm for four different matrices (i) C-1 (conventional concrete 100% NCA), (ii)C2 (50% TRCA +50% NCA containing concrete) (iii)C-3 (50% TRCA+30% NCA+20% RCA containing concrete) and (iv) C-4 (80% NCA +20% RCA containing concrete). The FEA package ABAQUS 6.14 was used for the analytical analysis of axial compression behaviour of recycled aggregate columns.

4.1 Material Properties and constitutive Models used

4.1.1 Concrete

Concrete is defined as an isotropic material before yielding and cracking model is defined for nonlinear analysis. 3D solid element is used for modelling of concrete as C3D8R which indicates eight nodes in three degrees of freedom in x,y and z directions. The compressive strength obtained from experimental studies f_{ck} is 31.7N/mm^2. The linear properties used in ABAQUS 6.14 for the analytical analysis are shown in Table 1.

Table -1: Linear Properties of Concrete

Parameter	Value
Concrete Density	2500 kg/m^3
Young's Modulus	5000X$\sqrt{f_{ck}}$=28,151.37N/mm^2
Poisson's ratio	0.17

To predict the behaviour of concrete, non-linear analysis using Concrete damage plasticity model because it uses concepts of isotropic damage elasticity in conjunction with isotropic tensile and compressive plasticity to represent the inelastic behaviour of concrete.

The parameters for nonlinear behaviour of concrete used in ABAQUS 6.14 are shown below.

Table -2: Nonlinear properties of concrete

Parameter	Value
Dilation angel (φ)	35°
Plastic potential eccentricity (e)	0.1
Initial biaxial/uniaxial ratio (f_{bo} / f_{co})	1.16
Shape of the loading surface (K_c)	0.66
Viscosity parameters	0

The stress strain relationship for compressive behaviour of concrete is derived from the relationship proposed using stress strain in uni axial compression by Saenz[13]

$$\sigma_c = \frac{E_c \times \epsilon_c}{1 + (R + R_E - 2)\left(\frac{\epsilon_c}{\epsilon_0}\right) - (2R - 1)(\frac{\epsilon_c}{\epsilon_0})^2 + R(\frac{\epsilon_c}{\epsilon_0})^3}$$

where

$$R = \frac{R_E\,(R_\sigma - 1)}{(R_\epsilon - 1)^2} - \frac{1}{R_\epsilon},$$

$$R_E = \frac{E_c}{E_o}$$

σ_c = Stress in concrete
ϵ_c = Strain in concrete
E_c = Initial modulus of elasticity
f'_c = maximum compressive strength of concrete.
Strain ratio; $R_\epsilon = \epsilon_f / \epsilon_0 = 4$
Stress ratio; $R_\sigma = f'_c / \sigma_f = 4$
ϵ_f and σ_f are maximum strain and corresponding stress on the uniaxial stress-strain curve
ϵ_0 = Strain corresponding to f'_c in a uniaxial compressive test = 0.0025.
Secant Modulus: $E_0 = f'_c / \epsilon_0$

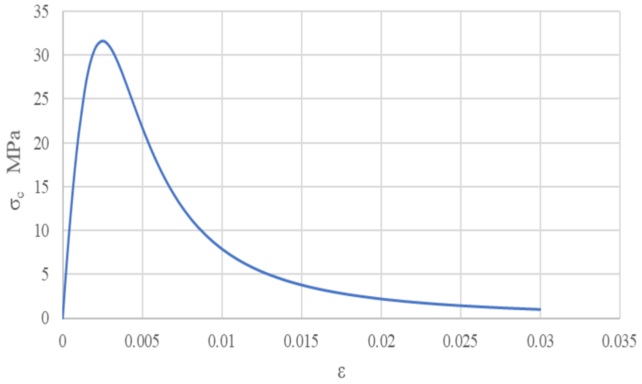


Fig -3. Stress-strain relationship of concrete under uniaxial compression by Saenz[13]

The tensile strength of concrete f_{cr} is calculated as per IS 456:2000[15] The tensile behaviour of concrete is obtained by the stress strain relation under uni axial tension proposed by Massicotte[14] as shown in Figure

$f_{cr} = 0.7 \text{ X } \sqrt{f_{ck}} = 3.94 \text{ N/mm}^2$

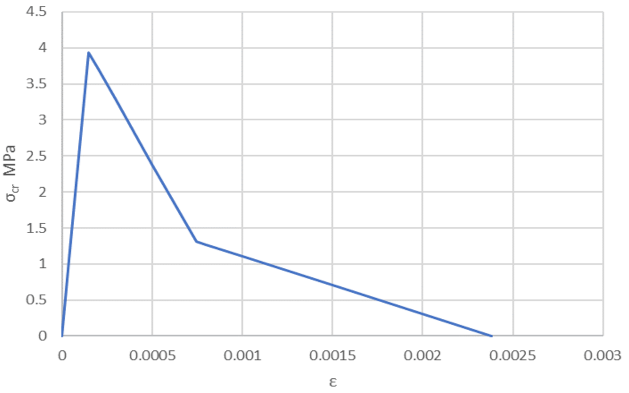


Fig 4: Stress-strain relationship of concrete under uniaxial tension by Massicotte[14]

4.1.2 Steel

Steel reinforcement was modelled as 3D truss element as T3D2 having 2 node displacement and assumed to be elastic perfectly plastic material. The reinforcement steel used in the present investigation is HYSD bars having yield strength f_y = 500 N/mm² and elastic modulus E_s = 200 GPa. A poisson's ratio of 0.3 was used for steel reinforcement.

The model is assembled using translation and rotation options in ABAQUS 6.14 according to their geometry as shown in Figure 5

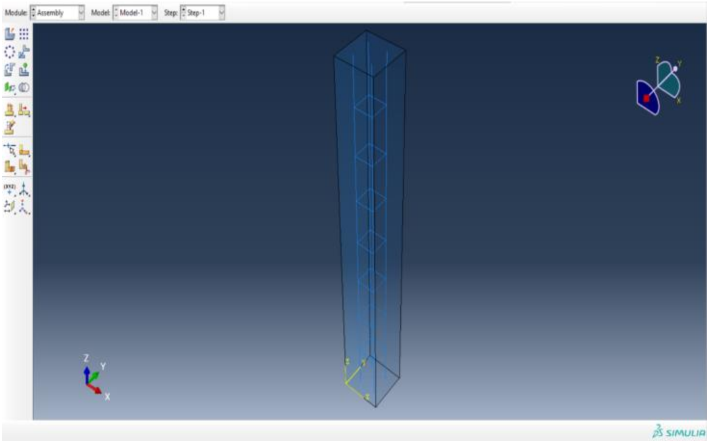

Module: Assembly
Model: Model-1
Step: Step-1

Fig -5: Modelling of column in ABAQUS 6.14

4.2 Numerical Analysis

The interface between steel reinforcement and concrete was considered as perfect bond. The steel reinforcement was embedded into the host region of concrete.

Meshing is important in the FEM analysis which comprise of shape and size of element. The meshing of model was done before loading condition and was discretized into finite elements. For solid element rectangular mesh of size 40mm was used as shown in Figure 6

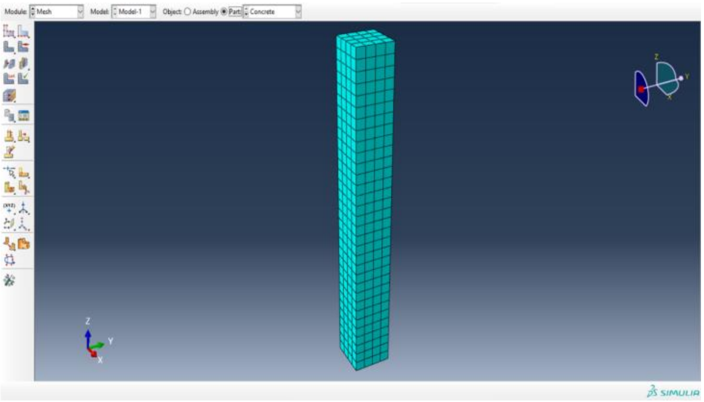

Module: Mesh
Model: Model-1
Object: ○ Assembly ● Part: Concrete

Fig -6: Meshing of column in ABAQUS 6.14

A pressure of 25N/mm^2 is applied at the top of the column. A fixed boundary condition is applied at the bottom of the column as shown in Figure 7

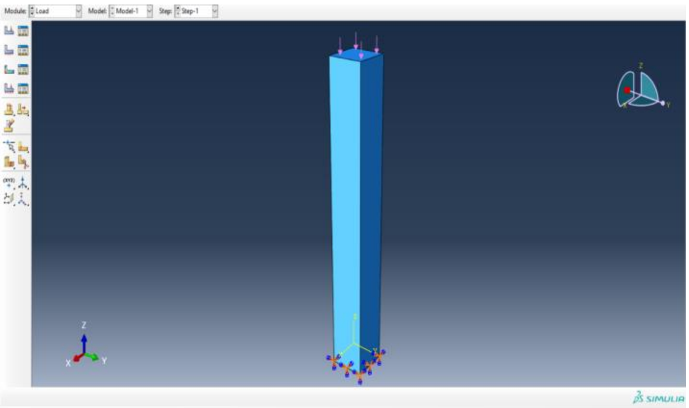


Fig -7: Loading and Boundary Conditions of column in ABAQUS 6.14

5. RESULTS

Analytical results of axial compression loading on recycled aggregate concrete columns using ABAQUS 6.14 for specimens (i) C-1 (conventional concrete 100% NCA), (ii)C2 (50% TRCA +50% NCA containing concrete) (iii)C-3 (50% TRCA+30% NCA+20% RCA containing concrete) and (iv) C-4 (80% NCA +20% RCA containing concrete) are shown below.

The analysis is run for the requisite parameters and models and the results are visualized in the ABAQUS 6.14. The obtained output results are, Reaction force shown in Figure 8 and deflection at 37.5mm from top of column shown in Figure 9 are plotted and then converted to stress and strain.

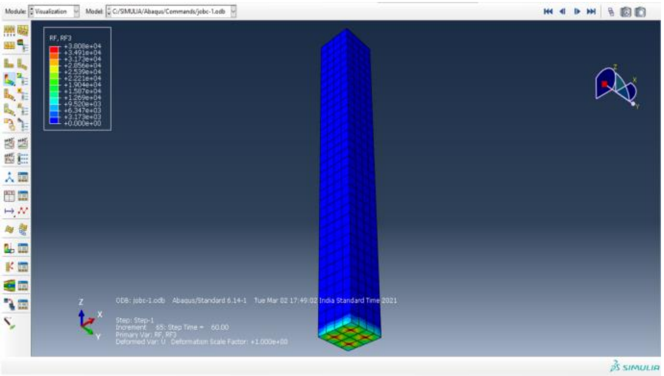


Fig 8: Reaction Force of column C-1(100% NCA) in ABAQUS 6.14

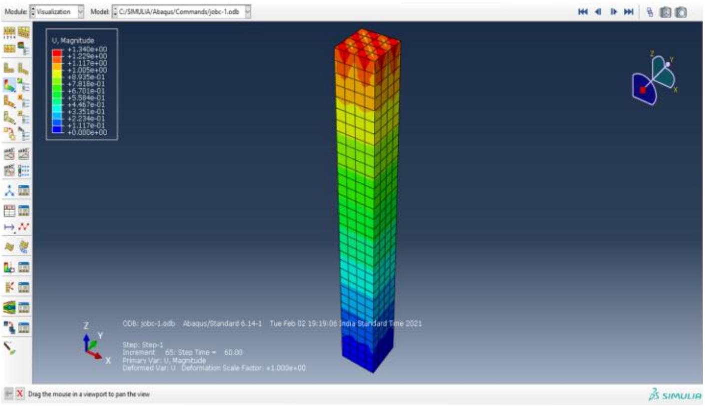


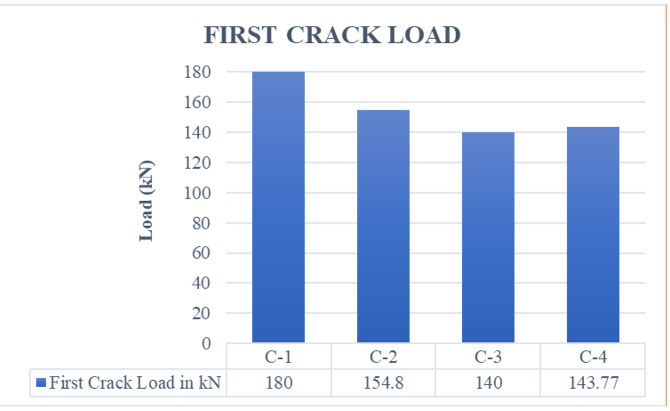
Fig -9: Deflection of column C-1(100% NCA) in ABAQUS 6.14

From observing stress versus strain curves from ABAQUS 6.14, the following data is obtained in the present investigation for column specimens of size 150 X 150 X 1200mm subjected to axial compressive load and the following results were investigated.

- First crack load
- Ultimate Load
- Behaviour of stress-strain curve
- Failure stresses
- Failure strains
- Comparison of experimental and analytical (ABAQUS 6.14) results

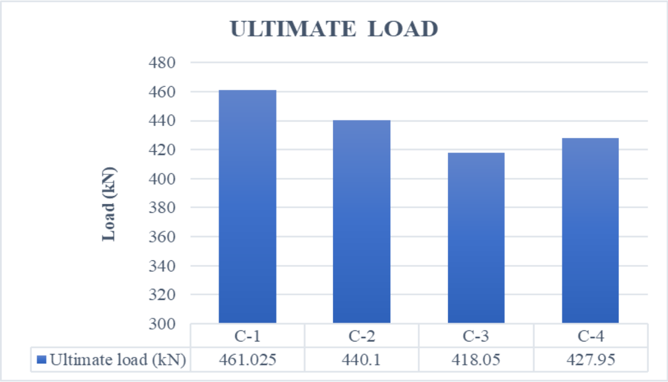
5.1 First crack Load

The first crack load is obtained from stress strain curve after axial compression analysis carried out in ABAQUS 6.14 are shown below



5.2 Ultimate load

The ultimate or failure load obtained for four different mixes are shown are shown below



5.3 Behaviour of Stress Strain curve

From the analytical analysis carried out in ABAQUS 6.14, the behaviour of the stress strain curve is plotted for all the columns as shown below

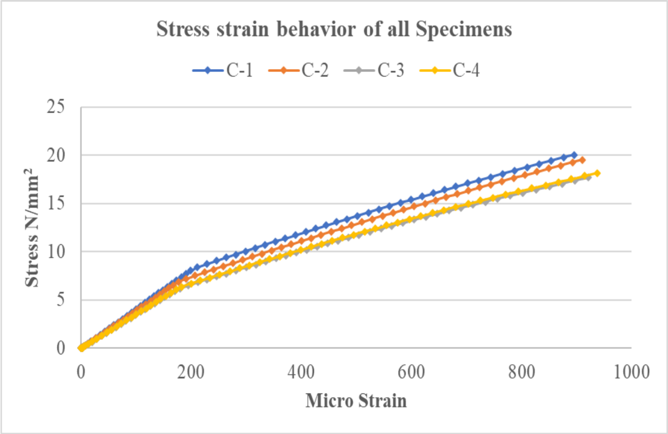
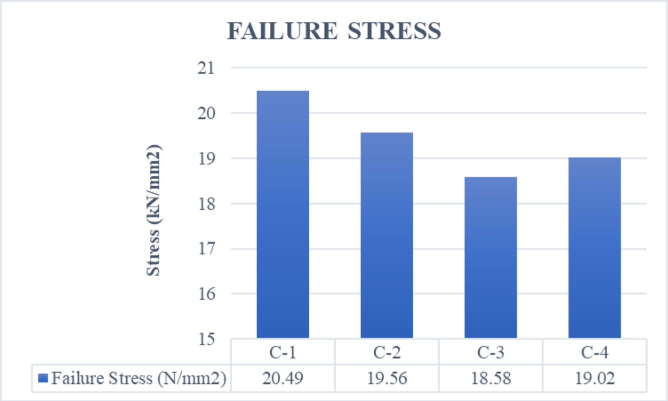


Fig -10: Analytical stress strain curve of all Specimens

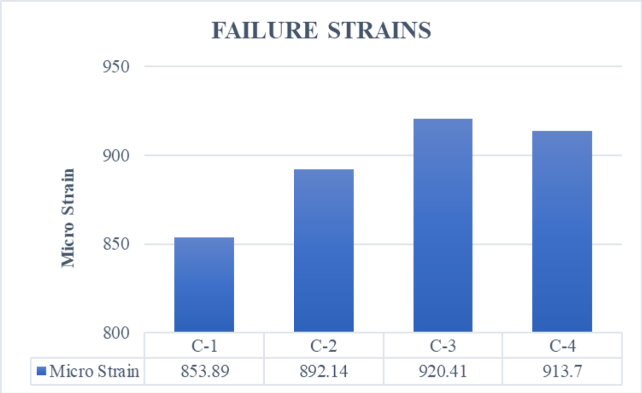
5.4 Failure stresses

From the obtained stress versus strain curves from ABAQUS 6.14, the Failure stresses which is used to calculate stress resistance capability are shown below



5.5 Failure Strains

From the obtained stress versus strain curves from ABAQUS 6.14, the Failure strains which is used to calculate maximum deflection are shown below



5.6 Comparison of experimental and analytical (ABAQUS 6.14) results

The analytical results obtained from ABAQUS 6.14 are compared with respect to the experimental results are as follows

5.6.1 Comparison of experimental and analytical First crack load

The analytical First crack load and experimental first crack load are compared and the ratio of experimental to analytical results (E/A) are shown below

Table -3: Comparison of First crack load

DESIGNATION	EXPERIMENTAL FIRST CRACK LOAD(kN)	ANALYTICAL FIRST CRACK LOAD(kN)	(E/A)
C-1	160	180	0.889
C-2	150	154.8	0.968
C-3	130	140	0.928
C-4	140	143.77	0.973

5.6.2 Comparison of experimental and analytical Ultimate load

The analytical Ultimate load and experimental Ultimate load are compared and the ratio of experimental to analytical results (E/A) are shown below

Table -4: Comparison of Ultimate load

DESIGNATION	EXPERIMENTAL FAILURE LOAD(kN)	ANALYTICAL FAILURE LOAD(kN)	E/A
C-1	450	461.02	0.976
C-2	430	440.10	0.977
C-3	410	418.05	0.981
C-4	420	427.95	0.981

5.6.3 Comparison of experimental and analytical Failure strain

The analytical Micro strain and experimental Micro strain are compared and the ratio of experimental to analytical results (E/A) are shown below

Table -5: Comparison of Micro strain

DESIGNATION	EXPERIMENTAL MICRO STRAIN	ANALYTICAL MICRO STRAIN	E/A
C-1	762	853.89	0.892
C-2	768	892.14	0.861
C-3	813	920.41	0.883
C-4	782	913.7	0.855

5.6.4 Comparison of experimental and analytical Stress strain curve

The stress strain behaviour of experimental analysis and analytical analysis are compared for all the four specimens.

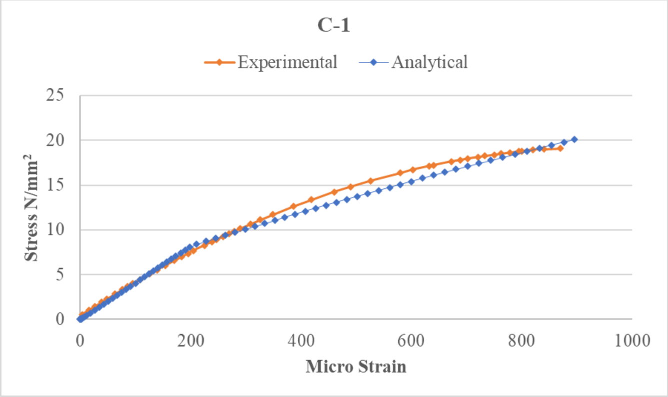


Fig -11: Comparison of stress strain curve for C-1:100%NCA

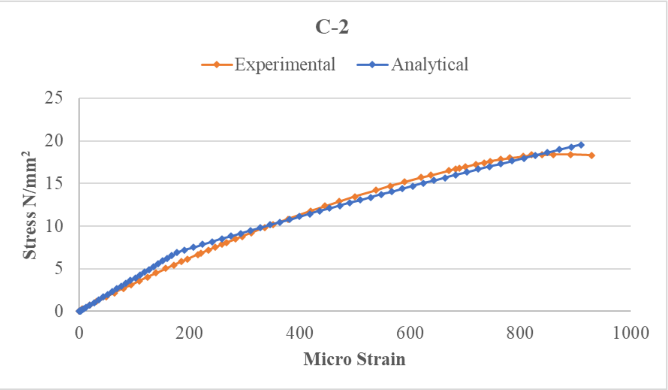


Fig -12: Comparison of stress strain curve for C-2: 50%TRCA+50%NCA

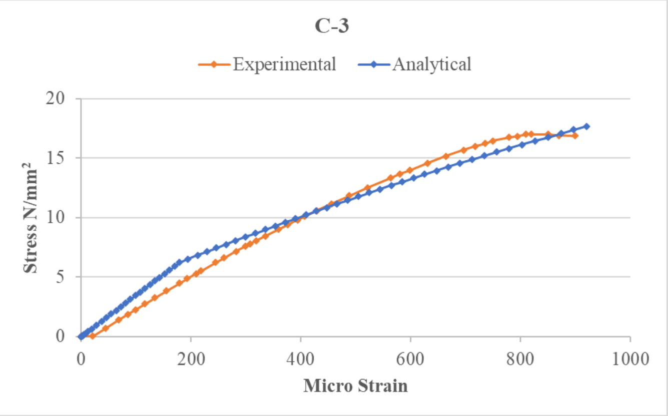


Fig -13: Comparison of Stress strain curve for C-3:50%TRCA+30%NCA+20%RCA

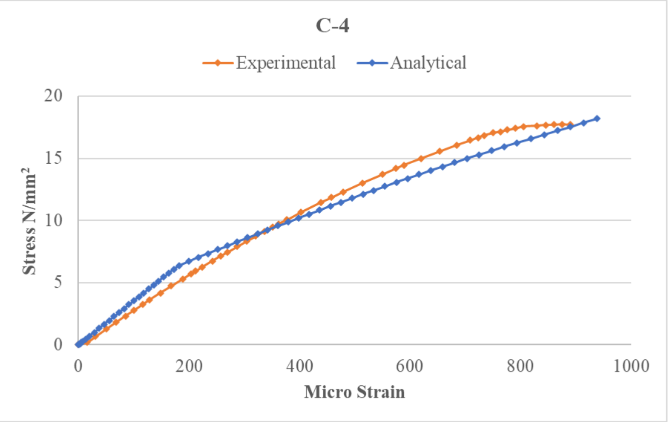


Fig -14: Comparison of stress strain curve for C-4: 80%NCA+20%RCA

The stress strain curves of C-1, C-2, C-3 and C-4 for both experimental and analytical analysis are compared and it can be seen that the analytical stress strain curve has similar trend with that of experimental stress strain curve of the recycled aggregate Column C-1, C-2, C-3 and C-4 respectively.

5.6.5 Comparison of experimental and analytical Young's Modulus

The experimental young's modulus and analytical young's modulus (ABAQUS 6.14) for the matrices used is calculated by finding the slope of stress-strain curve up to elastic point.

Table -6: Comparison of Young's Modulus

DESIGNATION	EXPERIMENTAL YOUNG'S MODULUS (kN/mm²)	ANALYTICAL YOUNG'S MODULUS (kN/mm²)	E/A
C-1	33.074	35.089	0.942
C-2	31.595	33.239	0.951
C-3	25.230	29.393	0.858
C-4	27.777	29.491	0.941

6. CONCLUSIONS

1. The first crack load for the C-1, C-2, C-3 and C-4 is 180 kN, 154.8 kN, 140 kN and 143.77 kN respectively. The percentage load decrease for different mixes with w.r.t C-1 (100% NCA) is 14%, 22.22% and 20.12% for C-2, C-3, and C-4 respectively. It is noted that the percentage load decrease for 50%TRCA+50%NCA (C-2) is less compare to other two mixes with reference to the conventional concrete(C-1). It is observed that C-2 has highest First crack load to 9.56% and 7.12% as compared with C-3 and C-4 respectively. The ratio of experimental to analytical first crack load for C-1, C-2, C-3 and C-4 is 0.889, 0.968, 0.928 and 0.973 respectively.

2. The ultimate or failure load obtained for the C-1, C-2, C-3 and C-4 is 461.025 kN, 440.1 kN, 418.05 kN and 427.95 kN respectively. The percentage load decrease for different matrices w.r.t to conventional concrete is 4.54%, 9.32% and 7.17% for C-2, C-3 and C-4 respectively. It is observed that C-2 has highest ultimate load to 5.16% and 2.92% as compared with C-3 and C-4 respectively. The percentage change of analytical to experimental failure load for C-1, C-2, C-3 and C-4 is 2.39%, 2.29%, 1.92% and 1.85% respectively.

3. The stress developed at failure point for C-1, C-2, C-3 and C-4 is 20.49 N/mm², 19.56 N/mm², 18.58 N/mm² and 19.02 N/mm² respectively. It is observed that the decrease in stress resistance for C-2, C-3 and C-4 is 4.54%, 9.32% and 7.17% respectively w.r.t C-1. The results shows that the C-2 (50%NCA+50%TRCA) has more stress resistance capacity compare to C-3 and C-4 w.r.t C-1. Hence C-2 shown comparable results with C-1.

4. The value of micro strain at failure load is 853.89, 892.14, 920.41 and 913.7 for C-1, C-2, C-3 and C-4 respectively. It is observed that C-1 has shown less strain compare to all specimens and C-3 has more strain value. And it is noted that strain value of C-2 has given comparable values with C1. The ratio of experimental to analytical micro strain for C-1, C-2, C-3 and C-4 is 0.892, 0.861, 0.883 and 0.855 respectively.

5. The analytical young's modulus for C-1, C-2, C-3 and C-4 are 35.089 kN/mm², 33.239 kN/mm², 29.393 kN/mm² and 29.491 kN/mm² respectively. The ratio of experimental to analytical young's modulus for C-1, C-2, C-3 and C-4 is 0.942, 0.951, 0.858 and 0.941 respectively.

It is evident from the analytical results, test column specimen C-2 has attained maximum First crack load, ultimate load and Stress Strain behaviour w.r.t column specimen C-3 and C-4. The analytically ABAQUS 6.14 results and experimental obtained results for axial compression behaviour of recycled aggregate concrete column test specimens are in good agreement.

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