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EXPERIMENTAL AND ANALYTICAL INVESTIGATION INVESTIGATION OF AXIAL COMPRESSION BEHAVIOR OF SHORT COLUMNS WITH RECYCLED COARSE AGGREGATE

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ABSTRACT

The behavior of axially loaded columns constructed from recycled coarse aggregates (RCA) was studied. Two different concrete mixes with varying ratios of RCA (0, 20, 40 and 60%) are conducted to achieve a compressive strength of 35 MPa. The test variables include the two different mixtures and replacement ratio of RCA. The results of specimens with RCA not more than 40%, showed that the structural performance of specimens using superplasticizer was similar to that of natural aggregate concrete specimens. The specimens were analyzed using the finite element *program ABAQUS (version 6.14). The models show acceptable correlation and are used to conduct a thorough parametric study on various design configurations. It is found that increasing the ratio of RCA plays a significant role in decreasing the columns ultimate capacities especially when the ratio exceeds 40%. .*

Keywords: Construction and demolition waste; Superplastizer; natural aggregate concrete Recycled coarse aggregate.

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1. INTRODUCTION

The global demand for construction aggregates is increasing tenuously. In Egypt there is a significance increase in the use of natural aggregates due to infrastructure and construction development. On the other hand, there are large amounts of debris from construction and demolition waste. The annual amount of construction and demolition waste in Egypt is 4.0 million tons [1]. While the current method of managing such waste is through disposal in landfills causing huge deposits of CDW and becoming an environmental problem. Recycling old elements from CDW is the most widely solution for this problem. The use of such waste in structural composite materials, such as concrete is becoming increasingly popular. Recycled concrete aggregate which is obtained by crushing old concrete elements from CDW, has been considered an alternative aggregate material for the use in structural concrete to achieve the sustainability of resources in construction industry. Recycled coarse aggregate (RCA) is an environmentally friendly concrete, which partly or totally substitutes natural aggregates (NCA) with (RCA) in the concrete mix. The application of RCA in the construction industry is a highly promising technology for conserving natural resources and minimizing the impact of urbanization.

The use of recycled materials was first introduced in Europe after the Second World War. Recycled waste industries are well established to utilize waste materials in new constructions. Most of the demolished structures, at that time, were concrete rubbles and they crushed ones were employed as a replacement of aggregates in concrete or as a sub-base pavement after they were sieved and separated from other materials [2, 3].

Despite being economical and environmentally friendly, the properties of recycled aggregates are different from those of natural ones. Previous studies have shown that recycled aggregates are smaller, weaker, more porous, and more water absorptive as compared with natural aggregates [4]. This is hardly surprising due to the grinding process associated with the production of recycled aggregates along with the concrete paste attached to them [5]. Therefore, these studies have suggested limiting the amount of recycled aggregates in the concrete mixture. It has been recommended that the optimum amount of recycled aggregates concerning the total aggregates amount in the concrete mix are 30% and 20% for recycled coarse and fine aggregate, respectively. Higher than these limits would reduce the strength of concrete [6, 7].

The main purpose of this work is to determine the basic properties of recycled coarse aggregate concrete, and to compare them to the properties of concrete made with natural aggregate. In addition, the mechanical properties of reinforced concrete columns with different percentages of recycled coarse aggregate under axial compressive load and compare them with the properties of standard specimens (100% NA) RC columns. This is to determine the suitability of using recycled aggregates in structural concrete and thereby reducing the burned on natural resources and ultimately providing environmental sustainability.

2. EXPERIMENTAL PROGRAM

2.1. Materials

Cement used in this study is the ordinary Portland Cement produced by Suez Cement Company which complies with the Egyptian Standard Specification ESS 4576-1 / 2009 [8]. Clean drinking fresh water free from impurities was used for mixing and curing the tested samples. The fine aggregate used in the experimental program was natural siliceous sand with specific gravity of 2.85 t/m^3, which meets the requirement of the Egyptian Standard Specification (ESS. 1109/2008) [9]. The natural coarse aggregates used were dolomite. Testing of dolomite was carried out according to the ESS 1109/2002. Two nominal size of dolomite 10mm and 20mm were used.

The recycled coarse aggregates used in this study were produced by crushing the old concrete elements that were used in previous laboratory tests from the Housing and Building National Research Center. The produced recycled coarse aggregates have two nominal size 10mm and 20mm to match with natural coarse aggregate. Physical, mechanical and chemical properties of the recycled coarse aggregate are determined according to ESS 1109/2002. In order to obtain the same workability without increasing water, superplastizer admixture Sikament -163 M was used. Sikament -163M complies with the ASTM C 494 type F with the following properties:

- Appearance / Color : Brown liquid
- Density (at 20°C) : 1.200 ± 0.005 kg/I
- Compatibility: compatible with all types of Portland cement

Deformed high grade steel bars of 18 mm diameter was used as longitudinal reinforcement. The stirrups used were steel bars of 10 mm diameter. The actual yield strength and ultimate strength of steel bars were 400 MPa and 600 MPa respectively.

2.2. Mix properties:

Two concrete mixes were used in this study with different percentage of recycled coarse aggregate (0, 20, 40 and 60 %) for studying the influence of recycled coarse aggregate on the fresh and hardened concrete. Natural siliceous sand as a fine aggregates and natural crushed dolomite was used as a natural coarse aggregates. Superplastizer with 0.8% of cement content was added in mix (2) for enhancing the workability. The concrete mixes have been designed using the empirical method to develop average cubic strength of 35 MPa.

2.3. Preparation of Specimens:

Eight rectangular short column specimens forming two groups were designed in this study. Group one with four columns were casted with mix (1) and group two with four columns were casted with mix (2). Four recycled coarse aggregate replacement percentage (0, 20, 40 and 60%) were used for each group. All column specimens have the same cross section 25x25 cm and 100 cm height. They were reinforced with four longitudinal steel bars at 18 mm diameter, and stirrups with 10 mm diameter and 100 mm spacing as shown in Figure (1). Three cubes (150mm), three prisms (100×100×700 mm), and three cylinders (150× 300mm) were casted with each column as shown in Figure (2). All specimens were cured in the lab with wetted canvas at least 28 days before undertaking tests. The cubic quantities used in each column are listed in Table (1).

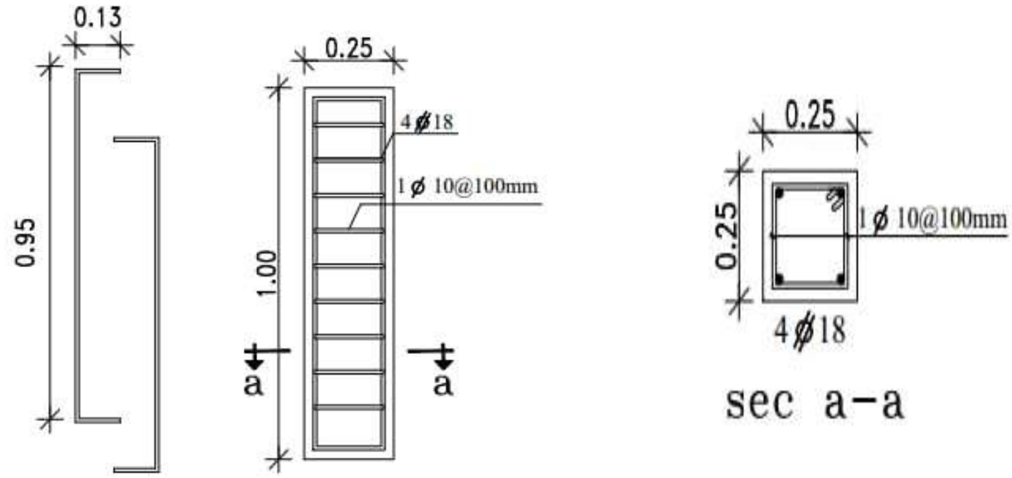


Figure (1): Details of reinforcement for column specimens

Figure (2): Casting of specimens

Table (1): Details of test specimens.

Group No	Col no		S/c ratio	cement kg/m^3	water kg/m^3	(W / c)	Sp kg/m^3	NCA kg/m^3	RAC kg/m^3	fc` MPa	F_{cu} MPa
G_1	C1		0.4 : 0.6	392	129.36	0.33	_	1208.7	_	31.2	40.8
	C2		0.4 :0.6	392	129.36	0.33	_	952.6	238.15	21.5	27.5
	C3		0.4 :0.6	392	129.36	0.33	_	706.92	471.28	26.8	35.2
	C4		0.4 :0.6	392	129.36	0.33	_	463	694.5	18.5	25.4
G_2	C5		0.4 :0.6	350	157.5	0.45	2.8	1182.1	_	32.3	41.4
	C6		0.4:0.6	350	157.5	0.45	2.8	930.72	232.68	32.6	42.3
	C7		0.4 :0.6	350	157.5	0.45	2.8	690.67	460.45	33	40.5
	C8		0.4 :0.6	350	157.5	0.45	2.8	453.26	679.9	26.8	34.2

Where sp. no is specimen number, S/C is sand to coarse aggregate ratio, sp is superplastizer weight, RAC is recycled coarse aggregate weight (10 – 20mm), NCA is natural coarse aggregate weight (10mm), f_C` is the nominal compressive strength of cylinders and f_{cu} is the compressive strength of cubes.

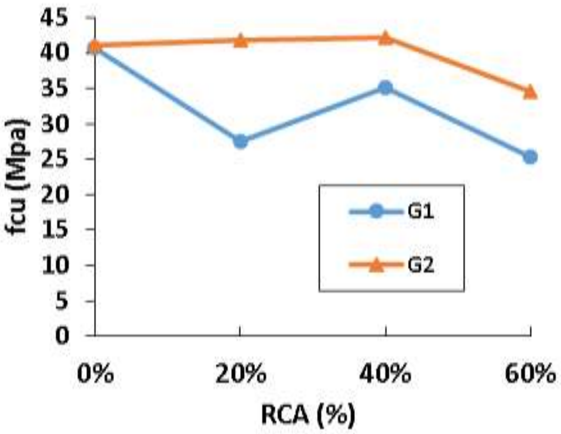
G1 refers to columns one to four casted of mix (1), G2 refers to columns five to eight casted Of mix (2).

3. MECHANICAL PROPERTIES OF CONCRETE

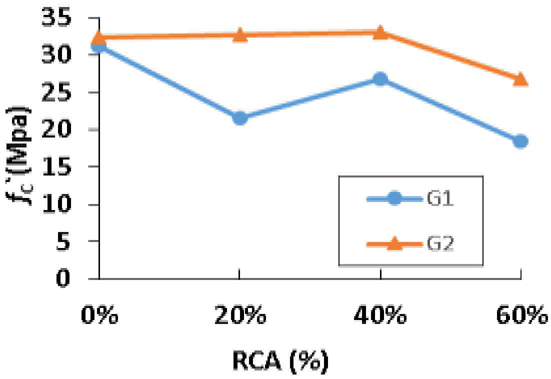
3.1 Compressive Strength

The cubes and cylinders were subjected to compressive strength test as shown in figure (3) at the age of 28 days from casting date. Figure 4 (a and b) show the influence of recycled coarse aggregate percentages on the compressive strength for the concrete mixes cubes and cylinders respectively.

Figure (3): Compressive strength test for cylinder.



(a)



(b)

Figure (4): Effect of recycled aggregate % on the compressive strength of the concrete mixes

It was observed that the compressive strength exhibited by 0% RCA was maximum. However, a significance decrease in compressive strength was observed as RCA replacement ratio increases which is in accordance with existing literature [6, 7].

3.2. Splitting Tensile Strength

Indirect tensile test was carried out as shown in figure (5) at the age of 28 days on twenty four cylinder specimens to determine tensile strength of concrete. Figures (6) shows the effect of recycled coarse aggregate percentage on the splitting tensile strength.

Figure (5): Splitting tensile test.

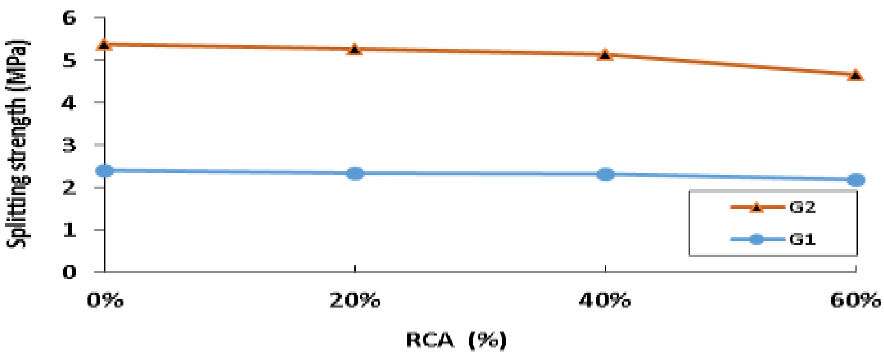


Figure (6): Effect of recycled aggregate percentages on splitting force

It can be seen that splitting tensile strength for recycled coarse aggregate concrete decreased when recycled aggregate was being used instead of virgin coarse aggregate. However, the reduction of the splitting tensile strength especially with using 20% and 40% replacement of RCA is not significance.

3.3. Flexural Strength

Twenty four prisms specimens were subjected to flexure testing to determine the flexural strength as shown in figure (7). The influence of recycled coarse aggregate percentages is shown in figure (8). It was noticed that increasing RCA replacement to 40% and 60% causes a significant decrease in the flexural strength (about 13 – 35%).

Figure (7): Flexural test.

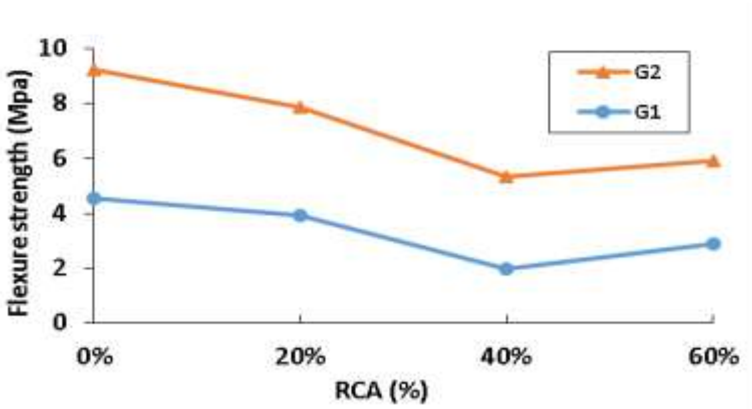


Figure (8). Effect of recycled aggregate percentage on flexure strength

4. COLUMNS TEST

4.1. Testing Procedure

The column specimens were tested using a rigid hydraulic jack with a maximum capacity of 5000KN. The specimen was placed between the heads of the compression machine and centered with the axis of the applied load to ensure uniform load distribution. The cross head was screwed down by the electrical motor until it touch the specimen. Zero readings of steel strains and axial concrete displacement were recorded. The pressure pump was activated and the load was applied gradually till ultimate load. The load was increased by 20 ton increment. At each level of loading, total applied load, concrete axial displacement and steel stains were recorded. The test was terminated when the load dropped to about 45% of the ultimate load. An overall view of the test set up is shown in Figure (9).

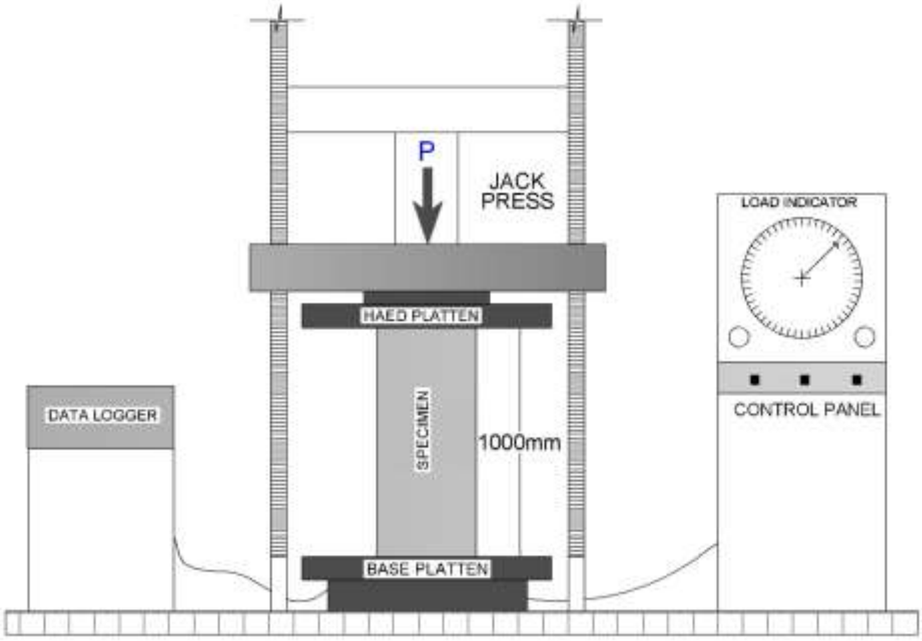
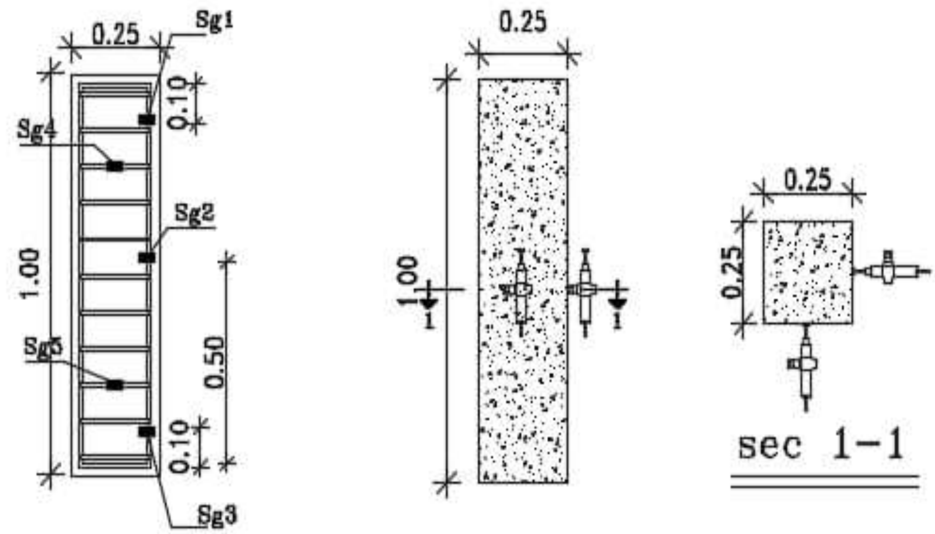


Figure (9): Test set up

4.2. Instrumentation

The concrete axial displacement was measured on two opposite sides of the specimen over the middle region using LVDTs. The concrete axial displacement was taken as the average of readings from both sides. Two electrical strain gages with 10 mm gage length were attached to the longitudinal reinforcements, in addition, two strain gages with 6 mm gage length were attached to the stirrups as shown in Figure (10). The electrical strain gages were used to measure stain in steel reinforcing bars. The strain gages, electrical pressure sensors, and LVDTs voltages were fed into the data acquisition system. The voltage excitations were read, transformed, and stored as micro strains, forces, and displacement by means of a virtual



instrument computer program that runs under Lab software.

Figure(10).Locations of strain gauges and LVDT

4.3.Mode of Failure:

Typical failure patterns were observed for all specimens as shown in figure (11). All columns failed at compression failure. Cracks initiated at the top and the bottom of columns, and then slantingly developed to the mid height. With increasing the load, cracks became wider. When the applied load approached the ultimate load, concrete cover at the mid height spalled off together with the yielding of longitudinal reinforcements, which resulted in a sudden loss of load capacity and failure of columns.

C_1 C_2 C_3 C_4

C_5 C_6 C_7 C_8

Figure (11): Failure modes for column specimens.

4.4. Axial load Capacities:

The failure load (P_f) and cracking (P_{cr}) loads for each column are listed in table (2).

Table (2). The failure and cracking loads for column specimens.

Group. No	Column No	fc` (Mpa)	Pcr (KN)	Pf (KN)	Pcr/ Pf
G1	C1	31.2	2310.5	2330.8	0.99
	C2	21.5	1820.5	1950	0.93
	C3	26.8	1670	2030.9	0.82
	C4	27.5	1510.4	1780.3	0.85
G2	C5	32.3	1700	2020.2	0.84
	C6	32.6	1950	2050.9	0.94
	C7	33	1750	2060.9	0.85
	C8	26.8	1800	1960.7	0.92

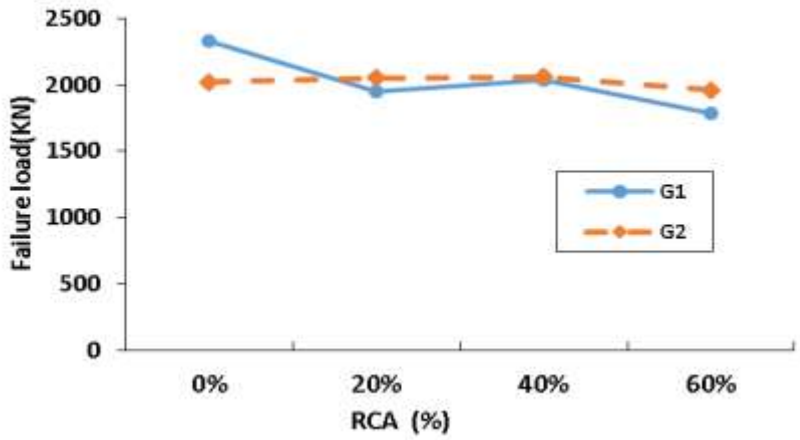


Figure (12): Effect of recycled coarse aggregate percentage on columns capacity

Figure (12) shows the impact of recycled coarse aggregate on the load carrying capacity of the column specimens. It was noticed that with the increase of RCA replacement ratio, the load carrying capacity of columns decreases. Columns which possessed RCA replacement ratio 20, 40 and 60% and casted with mix (1) recorded a decrease in load carrying capacity by 17%, 12.7%, and 23.7% respectively. Also, we can noticed that columns which possessed RCA replacement ratio 20% and 40% respectively have no influence in load carrying capacities.

4.5. Load – Displacement Curve

Figure (13) shows the relation between the vertical displacements at the mid height of column recorded by the LVDTs and the applied load for the two group of columns. It is observed that the ascending curve of all specimens follows the similar trend.

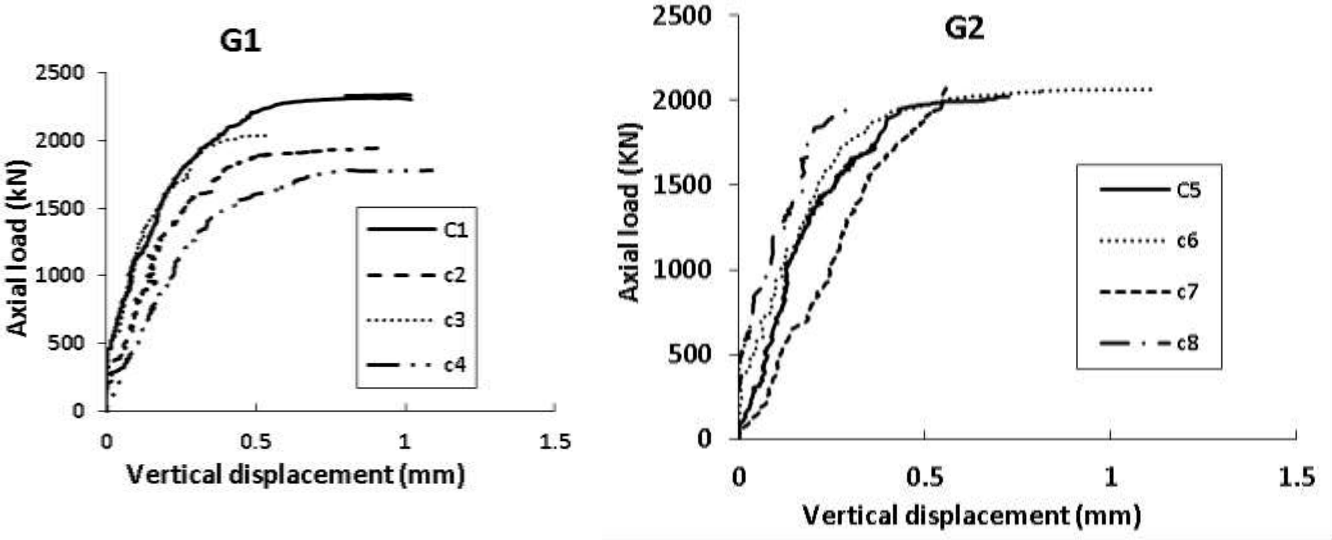


Figure (13): Axial load versus vertical displacement curves

4.6.Load – Strain Curve

Figure (14) shows the relation between the load and the strain readings from the longitudinal reinforcement, while figure (15) shows the relation between the load and the strain readings from the stirrups. It was observed that, load – strain curves for columns containing RCA in mix (2) have no significant difference in comparison to column with NCA. Also, it can be concluded that the longitudinal and the transverse reinforcement reached yielding before the ultimate load.

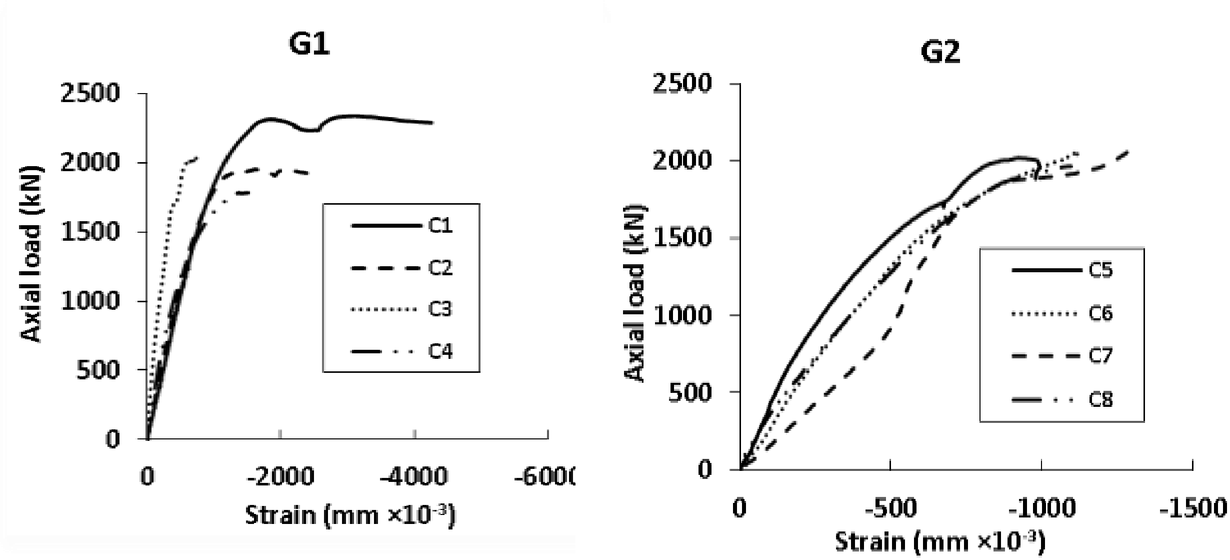


Figure (14): Axial load versus strain curves (longitudinal)

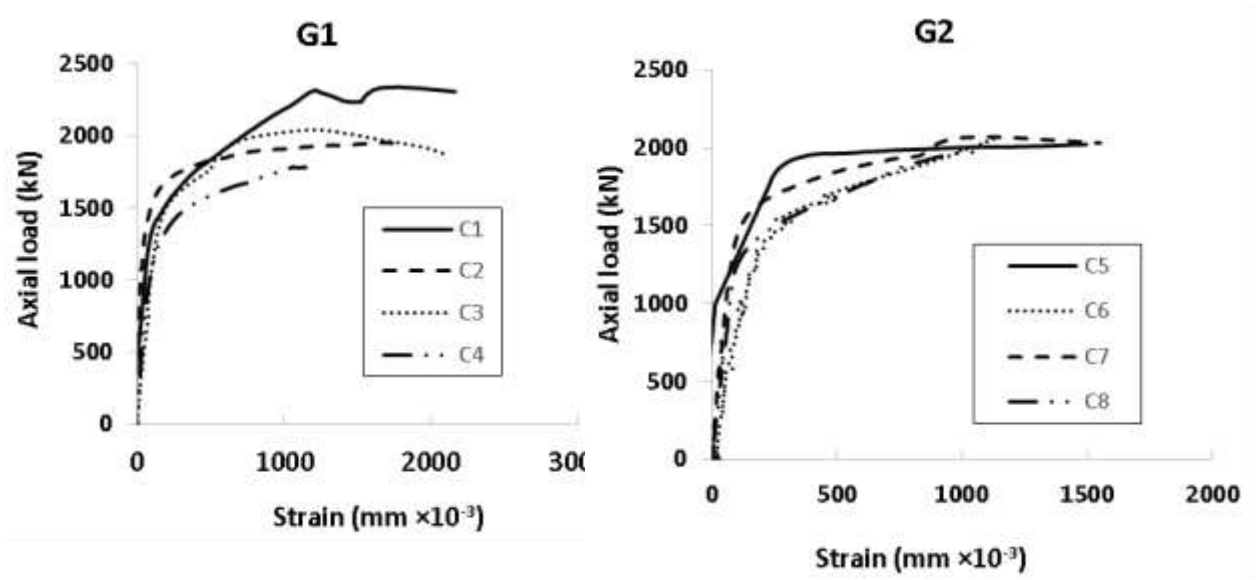


Figure (15): Axial load versus strain curves (stirrups)

4.7.Stiffness and Toughness

Initial axial Stiffness of the tested columns can be estimated by computing the average slope of the ascending part of the load – displacement curves. Therefore, the initial slope of the linear zone of the load – displacement curve between the point of about 10% of the maximum load and the point of about 30% of the maximum load was calculated [10]. A slight reduction of initial stiffness when using recycled coarse aggregate 20% and 40% can be observed from figure (16). Otherwise, using 60% recycled coarse aggregate recorded highest reduction of the initial stiffness by 59% and 30% for mix (1) and mix (2) respectively.

Toughness of the tested columns, which is the ability to absorb the energy through their deformations, is one of the main important characteristics of the structural behavior of the concrete elements. The toughness values can be represented by the total area under the load – displacement curves [10]. Comparing the toughness values in figure (15), it can be noticed that columns contain RCA percentage have reduction in toughness values about (19 – 54.8%). Otherwise, column C6 which possessed 20% RCA replacement ratio and casted with mix (2) recorded an increase of toughness by 77.8%.

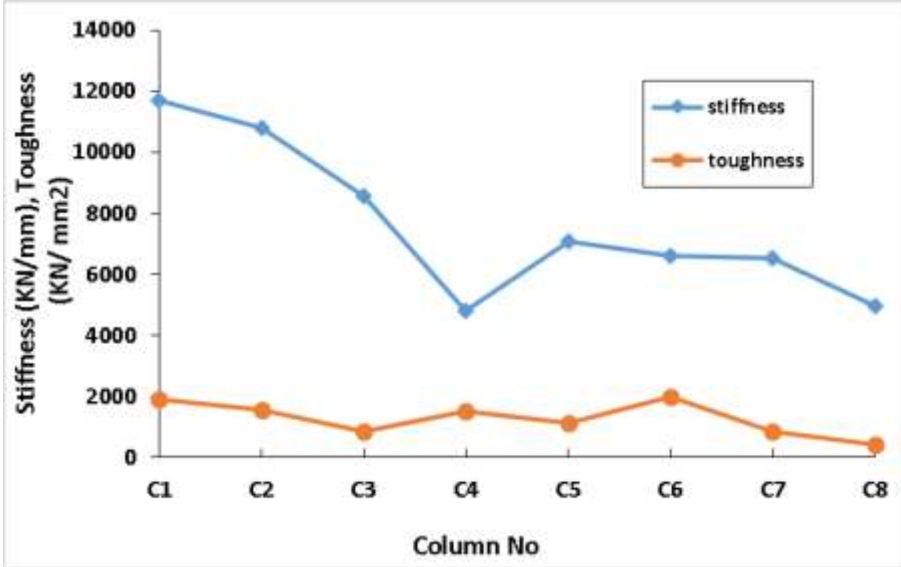


Figure (16): stiffness and toughness values of column specimens

5. NONLINEAR FINITE ELEMENTS

Commercial software package ABAQUS (Version 6.14) program [11] was used to investigate the behavior of the RCA columns under axial compression load. The investigated behavior includes the crack pattern, the max load capacity and the load-deflection response of the columns tested in the laboratory.

5.1.Geometry Modeling

The geometry of the column was modeled using eight – node three dimensional solid elements. The concrete part was modeled as an 8 – node linear 3D solid deformable part whereas the reinforcement were modeled using 2 – node linear deformable truss element.

The bottom end of the specimens was restrained in all directions for displacement and rotation, and the top end was kept free.

The bond between reinforcement and concrete was defined by using “embedded region constrains” available in ABAQUS which perfectly connects the degree of freedoms (DOF) of truss elements to the 8 – nodded brick elements of concrete.

Mesh sensitivity analysis was carried out to select the appropriate mesh size and simulate the experimental results with minimum computational time. 20mm mesh size was considered ideal in this model for all column specimens. Figure (17) shows the finite element model details.

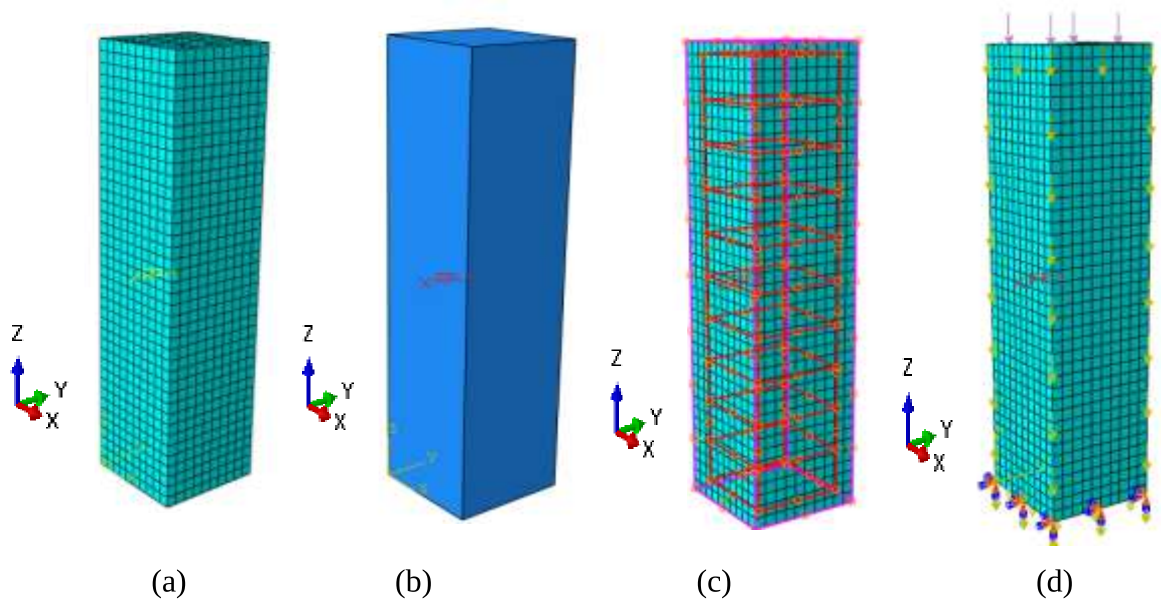


Figure (17): Finite element model, (a) meshed elements, (b) geometry, (c) embedded steel to concrete and constraints and (d) boundary conditions and loading.

5.2.Material Properties

Steel and concrete are the materials used in this model. For the concrete, the elastic behavior is defined through the modulus of elasticity and Poisson′s ratio while the inelastic behavior was defined using the concrete damage plasticity model (CDP). The elasticity and plasticity parameters are shown in table (4).

The material model used for steel reinforcement employs a uni-directional elastic-strain hardening response. The parameters to define this response are yield stress, (fy) of 400 MPa for 10 and 12 mm and 22 mm bars and elastic modulus (Es) of 200 GPa.

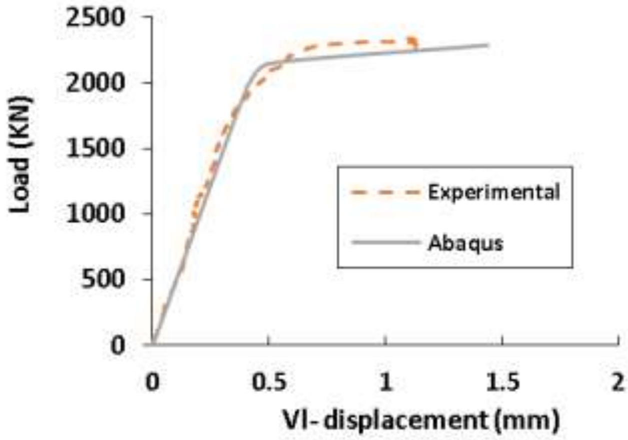
Table (4). Elasticity and plasticity parameters used in FE model

parameter	**value**	**description**
Ec	$5500\sqrt{f'_c}$	Modulus of elasticity
ν	0.2	Poisson′s ratio
ψ	30°	Dilation angle
∈	1.0	eccentricity
σb0/ σc0	1.16	Ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress
Kc	0.666	Ratio of second stress invariant on the tensile meridian that of compressive meridian.
μ	0.0001	viscosity

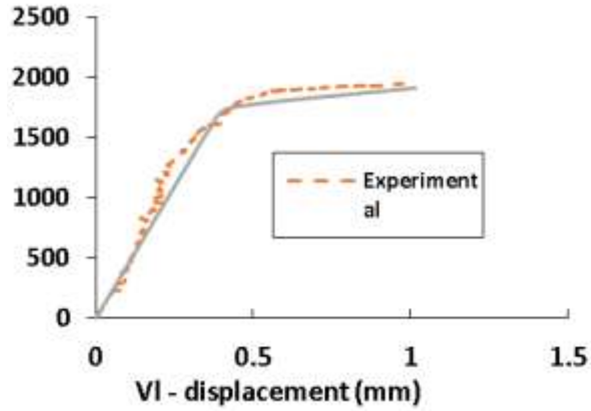
5.3. FE Model Verification

The predicted max load capacity and failure mode obtained from the model was examined against the test results for each column specimen. Figure 18 (a, b, c, d, e, f, g and h) show the load – displacement curves from the experimental and finite element model for C1, C2, C3, C4, C5, C6, C7 and C8 respectively. It is clear from figures that all FEM results are in a good agreement with the experimental results.

Table (5) shows the comparison of max capacity between all columns which are tested in the laboratory then analyzed in finite element.



(a)



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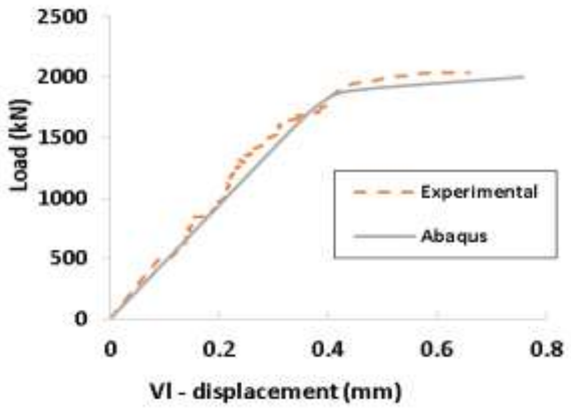
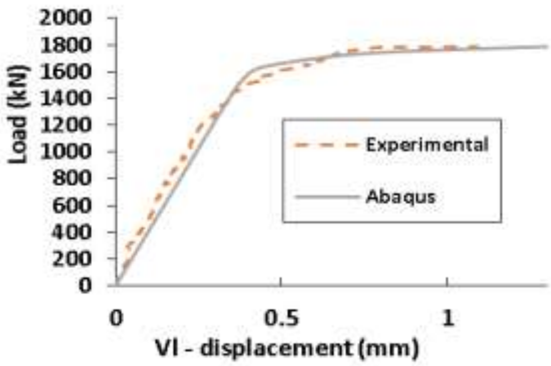


(c)



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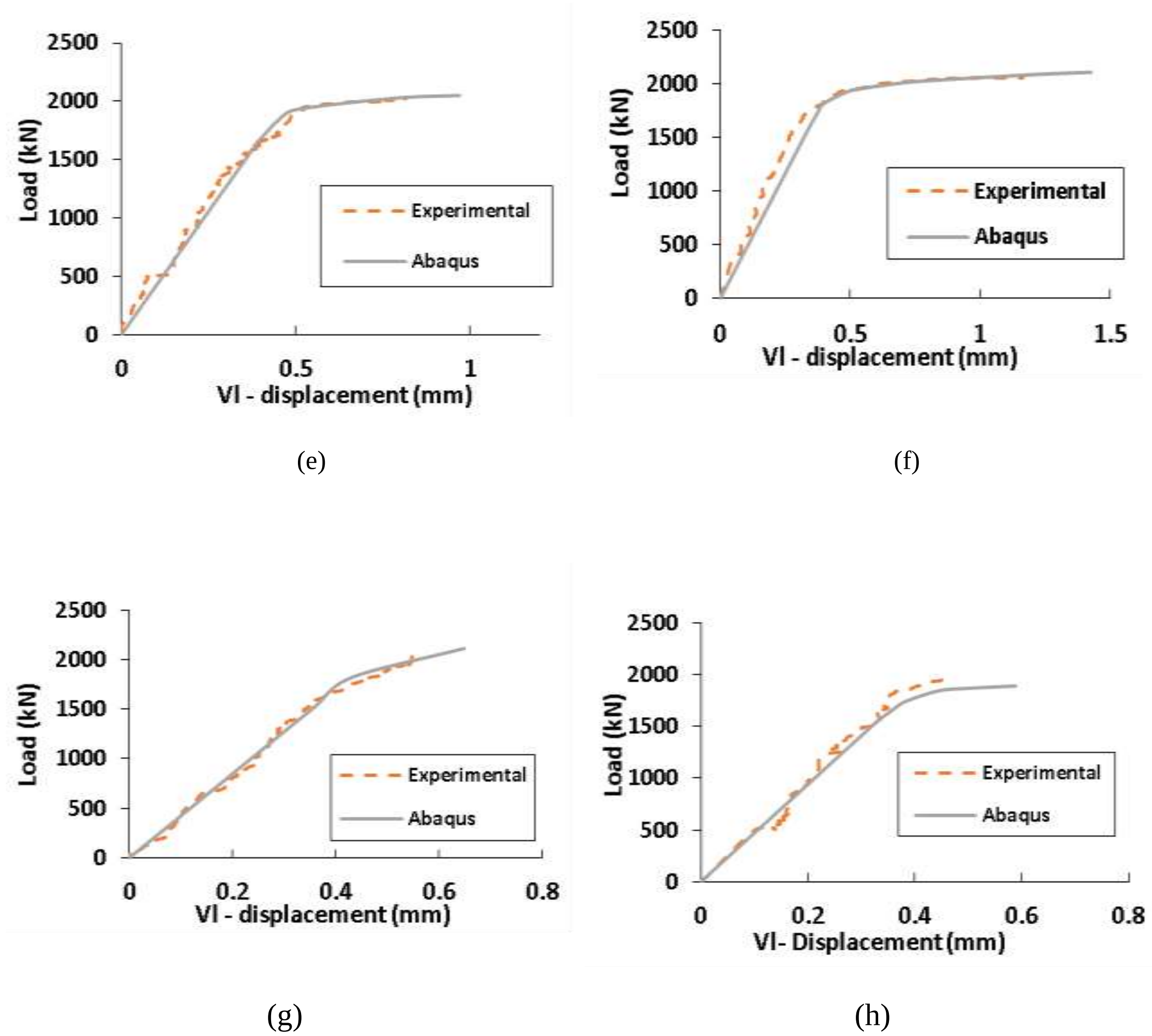


Figure (18): Comparison between EXP and ABAGUS curves for columns

Table (5). Comparison between ultimate load from experimental and ABAQUS

Group. no	Col. no	Ultimate load (KN)	FE load (KN)	Pu /P_{FE}
G1	C1	2330.8	2200	1.06
	C2	1950	1800	1.08
	C3	2030.9	1960	1.04
	C4	1780.3	1700	1.04
G2	C5	2020.2	1900	1.06
	C6	2050.9	2000	1.02
	C7	2060.9	1950	1.08
	C8	1960.7	1900	1.03

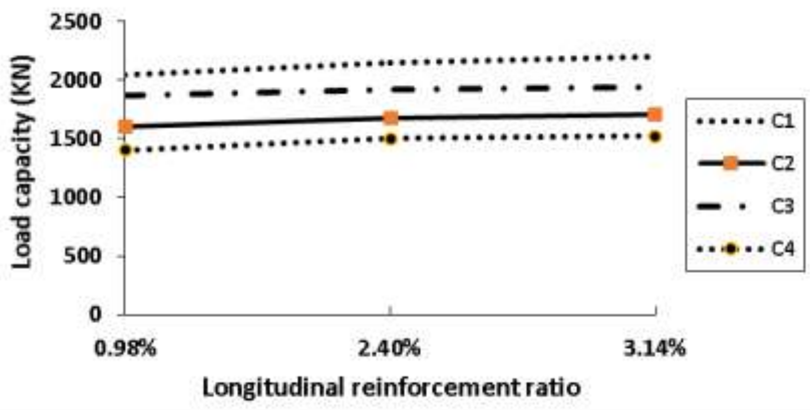
6. PARAMETRIC STUDY

It can be seen from the verification stage in the previous section, that the FE-models capture the structural behavior of the tested columns specimens in a satisfactory way. Therefore, a parametric study was conducted to complement the results of the existing experimental test database on the mechanical behavior of recycled concrete columns under concentric load. The following parameters were varied in order to carry out a complete parametric study

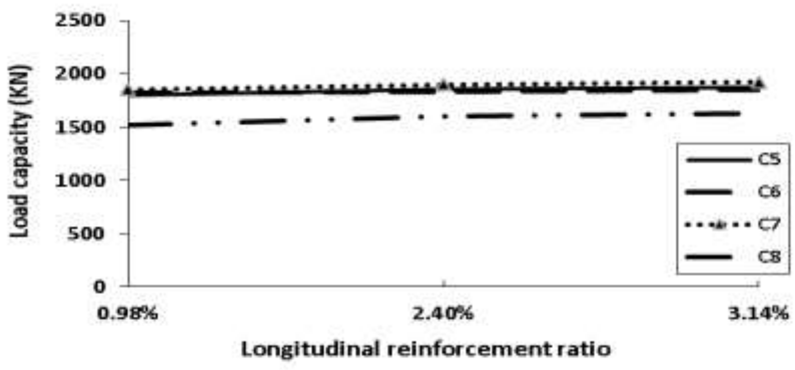
- The longitudinal steel reinforcement ratio
- The transverse steel reinforcement ratio
- Compressive strength of concrete

6.1.The Longitudinal Steel Reinforcement Ratio

Three different values of the longitudinal steel reinforcement ratio (ρ_s) were considered to examine their influence on the compressive behavior of the recycled concrete columns. The diameter of the longitudinal reinforcement was varied. The diameters considered are 14mm, 22mm and 25mm (corresponding to ρ_s of 0.98%, 2.4% and 3.14%). Figure 19 (a and b) shows the influence of the longitudinal reinforcement ratio on the load capacity of columns. It can be observed that using ρ_s = 0.98% decreases the load capacities of the RA columns by 10% and using ρ_s = 2.4%, 3.14% are similar and increasing the load capacity of RA columns by 8%.



(a)

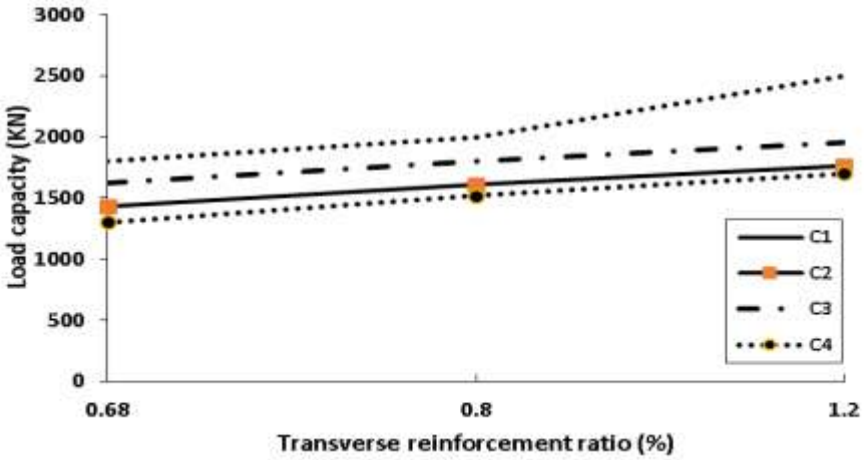


(b)

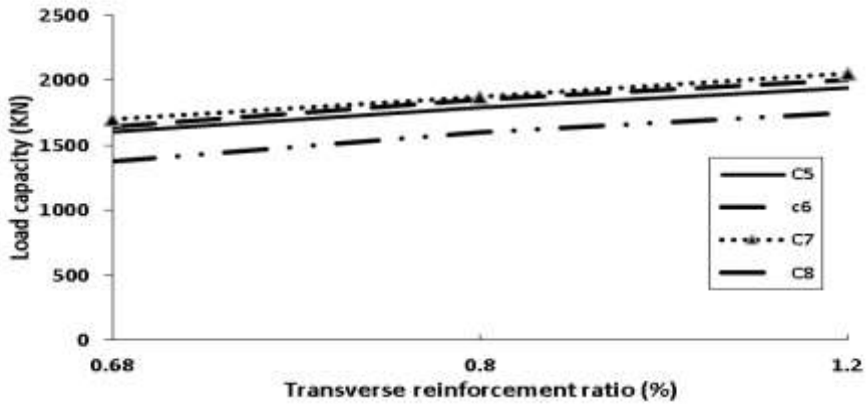
Figure (19): influence of longitudinal steel reinforcement ratio on load capacity of columns

6.2.The Transverse Steel Reinforcement Ratio

Three different values of the transverse steel reinforcement ratio (ρ_s) were considered to examine their influence on the compressive behavior of the recycled concrete columns. The diameter of the transverse reinforcement was varied. The diameters considered are 6mm, 8mm and 12mm (corresponding to ρ_s of 0.068%, 0.8% and 1.2%). Figure 20 (a and b) shows the influence of changing the transverse reinforcement ratio on the load capacity of columns. It can be seen that using diameter of 6mm and 8mm decrease the load capacity of columns by 22.7% and 14% respectively, but using diameter of 12mm increases the load capacity of columns by 7%.



(a)



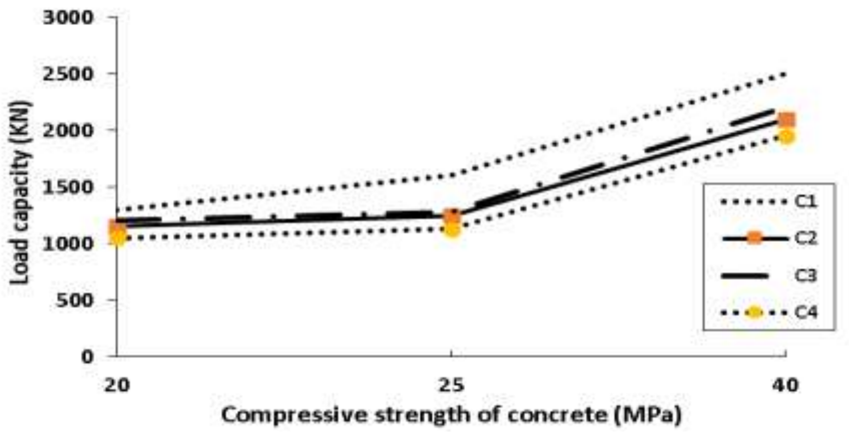
(b)

Figure (20): influence of transverse steel reinforcement ratio on load capacity of columns

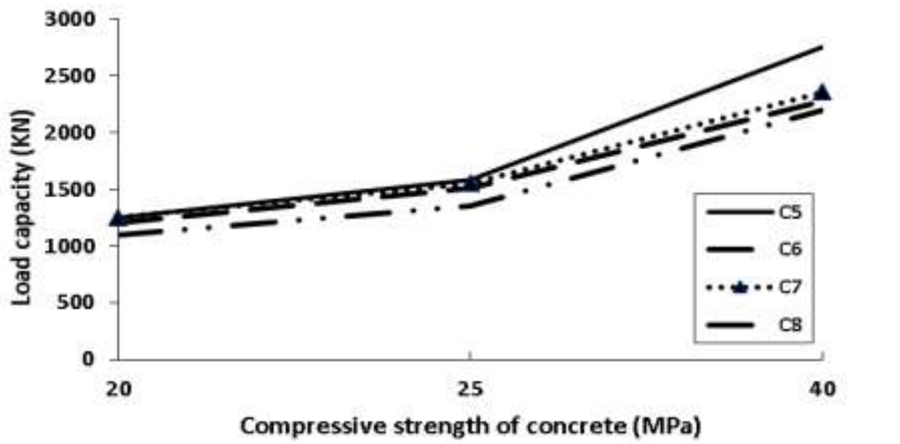
6.3.Compressive Strength of Concrete

The variable of the compressive strength of concrete (f_C`) can lead to change of the compressive capacities for the columns. Therefore, using compressive strength of 20, 25, and 40 Mpa was adopted in this model. Figure 21 (a and b) show the influence of changing the compressive strength on the load capacity of columns. It can be observed that increasing the compressive strength of concrete to 40 Mpa increased the load capacity of the columns by

40%. It can be also seen that the load capacity of the columns can be reduced by reducing the compressive strength to 20 and 25 Mpa by 25% and 12% respectively.



(a)



(b)

Figure (21): influence of compressive strength of concrete on load capacity of columns

7. CONCLUSIONS:

This study investigates the effect of replacing the natural coarse aggregate with recycled coarse aggregate on the structural behavior of short column under axial compression loading. Experiments were conducted on eight columns with different recycled coarse aggregate percentage and with two different mixes. The following conclusions may be drawn from the experimental and theoretical investigation.

1. A significance decrease in compressive strength was observed as RCA replacement ratio increases.
2. The splitting tensile strength was not significantly affected by using RCA up to a percentage of ratio 40%.
3. Flexure strength decreases as the recycled aggregate increases. The reduction of flexure strength are similar in the two mixes and recorded by approximately 13 – 35%.

4. The maximum axial load capacity decreases by 17%, 12.7%, and 23.7% for columns with 20%, 40%, and 60% RCA percentage ratios respectively.
5. The addition of superplastizer in mix (2) has no significant effect on the load axial capacity for columns which possessed recycled coarse aggregate with percentage 20% and 40% respectively.
6. The stiffness values are slightly reduced for columns containing 20% and 40% recycled coarse aggregate percentage. Columns containing 60% recycled coarse aggregate percentage have a reduction in stiffness values with 59% and 30% for mix (1) and mix (2) respectively.
7. Enhancement of toughness values by 77.8% for C6 which contain 20% recycled coarse aggregate percentage and superplastizer in mixture, but the remained columns recorded reduction in toughness values ranged between 25.3% to 63.2%.
8. A numerical model has been developed and validated that is capable of simulating the ultimate axial load capacity of short columns with recycled aggregate.

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