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Effect of Use Recycled Coarse Aggregate on the Behavior of Axially Loaded Reinforced Concrete Columns

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ABSTRACT

Nowadays, the use of recycled waste construction materials instead of aggregates is becoming popular in construction owing to its environmental benefits. This paper presents an experimental and analytical campaign to study the behavior of axially loaded columns constructed from recycled aggregates. The latter was used instead of natural aggregates, and they were collected from the waste of previous concrete constructions. Different concrete mixtures made from varying amounts of recycled aggregates ranged from 0 to 50% of the total coarse aggregate were conducted to achieve 28 MPa. The effect of steel fibers is another investigated variable with volumes ranged from 0 to 2% concerning concrete's mixture. The experimental results showed that the concrete strength is dependent on the amount of recycled aggregates. When the recycled aggregates were less than 30% of the total aggregates, they had a negligible effect on concrete strength and the load carrying capacity of the column models were improved. Also, the presence of steel fibers enhanced the load carrying capacity of the columns constructed from concrete with recycled aggregates of more than 30%. Finite element analysis (using ANSYS 16.1 software program) was conducted to simulate the experimental investigations, and they achieved good agreements with the test results.

Keywords: ANSYS, column, recycled aggregates, steel fiber, waste materials.

تأثير استخدام الركام الخشن المعاد تدويره على تصرف الأعمدة الخرسانية المسلحة محورية التحميل

عمر شمال فرحان
مدرس
هندسة مدني/ جامعة النهرين

الخلاصة

في الوقت الراهن، أصبح استخدام مواد البناء المعاد تدويرها بدلاً من الركام أمراً شائعاً في البناء بسبب فوائده البيئية. تم دراسة السلوك العملي والتحليلي لأعمدة خرسانية محورية التحميل باستبدال نسب من الركام بركام معاد تدويره. حيث تم استخدام نسب تتراوح من 0 إلى 50٪ من إجمالي الركام الخشن (الحصى) لتحقيق مقاومة خرسانة مقدارها 28 نت/ملم^2. إن تأثير الألياف الفولاذية هو متغير آخر تم فحصه بنسب تتراوح من 0 إلى 2٪. أظهرت النتائج التجريبية أن قوة الخرسانة تعتمد على كمية الركام المعاد تدويره. حيث عندما كانت نسبة الركام المعاد تدويره داخل الخلطة أقل من 30٪ من نسبة الركام الطبيعي، فان تأثير هذه النسبة ضئيل على قوة الخرسانة وتم تحسين قدرة تحمل الحمل الأقصى لنماذج الأعمدة. كذلك فإن وجود الألياف الفولاذية قد عزز القدرة على زيادة الحمل الأقصى للأعمدة التي تحتوي على نسبة ركام معاد تدويره لأكثر من 30٪. تم استخدام برنامج تحليل العناصر المحددة (ANSYS) وذلك لمحاكاة الجزء العملي وحققت توافقات جيدة مع النتائج العملية.

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الكلمات الرئيسية: عمود، مواد النفايات، الركام المعاد تدويره، الألياف الفولاذية، برنامج ANSYS.

1. INTRODUCTION

In Iraq, the significant presence of concrete blocks, and the large number probably to be utilized and re-used in concrete mixes instead, of course, aggregate (gravel) where the study of the subject of alternative gravel in reinforced concrete mixes from the practical and economic aspects. The demolition of old reinforced concrete structures would result in a large amount of waste material that would defiantly impose a severe threat to the environment, as shown in **Fig. 1**.

(A) (B)

Figure 1. (A) Demolition of building in Iraq, (B) Mechanisms for grinding concrete in the site.

From economic and environmental points of view, the use of recycled waste material would be essential. To that end, privet companies have replaced simple labors with advanced machinery to grind the old concrete and make full use of it. The mechanical properties recycled aggregate obtained from the waste concrete is quite different from those of natural aggregates. Therefore, it is necessary to build an understanding of their behavior if they were to be used in the concrete mix design. As can be seen from **Fig. 2**, the main difference between the natural and recycled aggregate is that the latter is usually attached with old cement mortar, some additives to the old concrete mixture such as fly ash, silica fume, or slag, and latex paint.

Figure 2. Recycled concrete aggregate**.**

The main objective of this study is to investigate the behavior of reinforced concrete columns constructed from various amount of recycled coarse aggregate to aid the understanding about the behavior of such sustainable material in terms of hardened concrete. Also, the effect of the use of steel fibers in recycled aggregates concrete mixtures will be investigated to enhance the strength of hardened concrete since steel fibers have been proved to increase the strength of concrete by minimizing the cracks and increase the ductility.

2. LITERATURE REVIEW

The use of recycled materials was first introduced in Europe after the 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, **Hansen, 1992**, **Mehta** and **Monteiro**, **1993**, **Collins, 1994**, and **Sherwood, 1998**.

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, **Hendriks** and **Pieterson, 1998**. This is hardly surprising due to the grinding process associated with the production of recycled aggregates along with the concrete paste attached to them, **Barra de Oliviera** and **Vasquez, 1996**. 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 due to the reasons explained above, **Katz, 2003, Chen, et al., 2003,** and **Dhir, et al., 1999.**

Also, unlike the quality of recycled aggregates, it was found that the strength of the concrete made from recycled aggregates is affected by the water/cement ratio. Such concrete was found to require high water/cement ratio than that made from natural aggregates which would consequently lead to a reduction in compressive strength, **Ryu, 2002**, and **Padmini, et al., 2002**. To achieve a strength comparable to the original concrete, a similar or less water/cement ratio must be used, **Chen et al., 2003, Dhir, et al., 1999**, and **Ryu, 2002**. The development of strength after 28 days, however, was found to higher than that made from natural aggregates, **Khatib, 2005**.

Properties including density, compressive strength, split tensile strength, flexural strength and modulus of elasticity are proved by the addition of steel fiber to concrete mixes to reduce concrete cracking and increased the ductility. **Efe** and **Musbau, 2011**, presented an experimental work on the effect of different steel fiber content and shape upon lateralized concrete columns, they concluded that there is a relationship between concrete strength and higher ultimate load.

Hadi, 2009 studied the effect of fiber on high strength concrete of circular reinforced concrete columns, where used three types (with fiber, without fiber and with fiber subjected at the outer size), the results show increasing in steel fiber content reduces carking and improve the ultimate load and ductility. **Campion et al., 2010** presented reinforced confined concrete columns with non-fiber or with regular fiber and high strength concrete with concentric and eccentric loading and effect of fibers on the thickness of columns cover.

Table 1 shows the variations of compressive strength of recycled aggregate concrete with different replacement levels compared to natural aggregate concrete for former researchers.

Table 1. Variation in compressive strength of recycled aggregate concrete a concrete.

Replacement level	Variation in compressive strength as compared to natural concrete	References
25 %	9 % Increase	**Etxberria, et al., 2007**
25 %	15 % Decrease	**Alam, et al., 2013**
30 %	10 % Decrease	**Yang, et al., 2008**
30 %	9.5 % Decrease	**Kwan, et al., 2012**
30 %	Similar	**Limbachiya, et al., 2000**
50 %	11 % Increase	**Etxberria, et al., 2007**
50 %	14.7 % Decrease	**Alam, et al., 2013**
50 %	5 % Decrease	**Yang, et al., 2008**
50 %	5 % Decrease	**Limbachiya, et al., 2000**
60 %	30 % Decrease	**Kwan, et al., 2012**
100 %	7.7 % Increase	**Etxberria, et al., 2007**
100 %	11 % Decrease	**Yang, et al., 2008**
100 %	2.4 % Increase	**Salem, et al., 2003**
100 %	8.9 % Increase	**Limbachiya, et al., 2000**
100 %	8 % Decrease	**Ajdukiewicz** and **Klizsczewicz, 2002**

Table 2 presents the differences in terms of tensile strength results of recycled aggregate concrete of previous tests. Tensile strength of recycled aggregate concrete is decreased with increased porosity.

Table 2. Variation in tensile strength of recycled aggregate concrete a concrete.

Replacement level	Variation in tensile strength as compared to natural concrete	References
15 %	Similar	**Gomez-Soberon, 2002**
25 %	6 % Increase	**Etxberria, et al., 2007**
25 %	34 % Increase	**Alam, et al., 2013**
30 %	2.7 % Decrease	**Gomez-Soberon 2002**
50 %	18 % Increase	**Etxberria, et al., 2007**
50 %	16 % Increase	**Alam, et al., 2013**
60 %	8 % Decrease	**Gomez-Soberon 2002**
100 %	2 % Decrease	**Etxberria, et al., 2007**
100 %	10.8 % Decrease	**Gomez-Soberon 2002**

3. PHYSICAL AND MECHANICAL PROPERTIES OF RECYCLED AGGREGATE CONCRETE

The previous study of **Chen, et al., 2003** has demonstrated that the use of washed recycled aggregates in the concrete mixture has resulted in a high compressive strength as compared with the unwashed ones. Two reasons are behind such strength enhancement: the increment of bond and the reduction of the required amount of water to produce workable concrete as the waste materials attached to the recycled aggregate have been removed by washing.

The use of recycled aggregate from local landfills would contribute to a reduction in high transportation costs currently incurred through the use of natural aggregate. **Abbas, et al., 2009** found the physical properties of recycled aggregate concrete are affected by the residual mortar quantity and characteristics, this method can directly account for any deficiencies low-quality aggregate, balancing the mix without affecting the mechanical and durability-related performance of the final concrete. This allows the recycled aggregate concrete mix to be prepared with a similar internal structure to that of natural aggregate concrete.
Akbari, et al., 2011 studied the effect of recycled aggregate concrete on the mechanical properties of fresh and hardened concrete. **Akbari**'s study has shown that concrete made from 100% recycled aggregates exhibited a 12.2% and 8.2% increase in concrete strength and permeability as compared to that made from natural aggregates. And, a 17.7% reduction in modulus of elasticity, as compared to that made from natural aggregates. **Umoh, 2012** found Reductions in terms of compressive and flexural strengths, and workability of concrete when recycled aggregates were used as compared to those of concrete made from natural aggregates.

4. WATER ABSORPTION

One of the most important problems of recycled aggregate is the absorption of water, where all the previous researches showed a higher water absorption rate than regular concrete (that contained normal aggregate). This is because the original cement mortar in recycled aggregate has a porosity higher than the natural gravel, this will affect the concrete density whereby its porosity primarily depends on the W/C ratio of the original (old) concrete. Thus, the absorption of water of recycled aggregate is even greater, as the quantity of mortar, which is attached grains of the original recycled aggregate increases.
It has been shown in practice that the stated amount of cement mortar in recycled aggregate ranges from 25% to 65% (in volume percentage) and that it differs in certain fractions – the smaller the portion, the higher the amount of cement mortar, as well as the level of water absorption, **Marinkovic, 2009**. Also, the analyses undertaken in extensive research around the world indicate that the stated amount of old cement mortar depends on the crushing method in the recycling process, thereby, according to some researchers, the maximum amount of mortar layer in recycled aggregate is recommended to less than 44% for constructional concrete. Additionally, the researchers from the University of Hong Kong recommend that the amount of recycled aggregate in structural concrete should range from 20% to 30%, to ensure that the maximum water absorption of aggregate used is less than 5%, **Jevtic, et al., 2009**.

5. EXPERIMENTAL PROGRAM

The experimental program consists of casting and testing eight identical short column specimens of the (100*100*700 mm) with different recycled aggregate replacement levels of (0, 10, 20, 30, 40 and 50%). Also, a percentage of steel fiber was added to the specimens in which the compression strength was reduced when the replacement of coarse aggregate, the percentage of steel fiber which used (0, 1 and 2%) to the concrete mix to investigate the difference in the behavior of these specimens when subjected to axial loading. The experimental program consists of control column was casting and testing with natural aggregate without recycled aggregate to comparison with other columns that contained recycled aggregate. All columns specimens have a top and bottom bearing rubber of 2 mm thick plate to prevent end bearing failure of the two ends and to ensure that the load is distributed uniformly overall the column ends. All specimens were reinforced with four longitudinal steel bars of 10 mm diameter (with 4-φ10 mm). Ties were made of (φ4 mm) bar diameter and spaced at (75 mm) in all the specimens, and the clear cover was (6mm), as shown in **Fig. 3**.

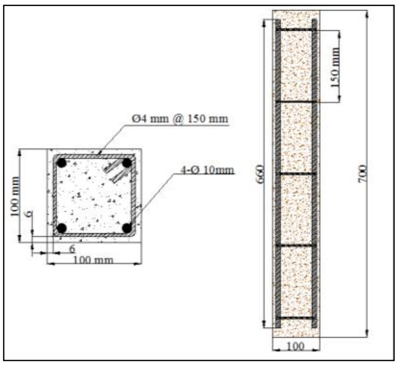


Figure 3. Details dimensions and reinforcement of the tested column.

6. DESCRIPTION OF MATERIALS AND PROPERTIES

6.1 Cement

All specimens reported in the study were constructed using Ordinary Portland cement type I from a local manufacturer and conform to the **Iraqi specification No.5/1984**.

6.2 Fine Aggregate

The fine aggregates used to construct the specimens were tested to determine their mechanical and chemical properties and conform to the **Iraqi Specification No.45/1984** (zone 2).

6.3 Natural Coarse Aggregate

The coarse aggregates used to construct the specimens are crushed to natural ones with a maximum size of 10 mm. The grading of this type of aggregate was conforming according to the **Iraqi specification No.45/1984**.

6.4 Recycled Coarse Aggregate

The crushed plain concrete used in the study was obtained from recycling the pre-tested regular concrete cubes and cylinders which was available in the laboratory. The process involves crushing and classification of aggregate to different grades based on particle size with a maximum size of 10 mm to match with natural coarse aggregate, as shown in **Fig. 4**. **Table 3** shows the grading of natural and recycled coarse aggregate.

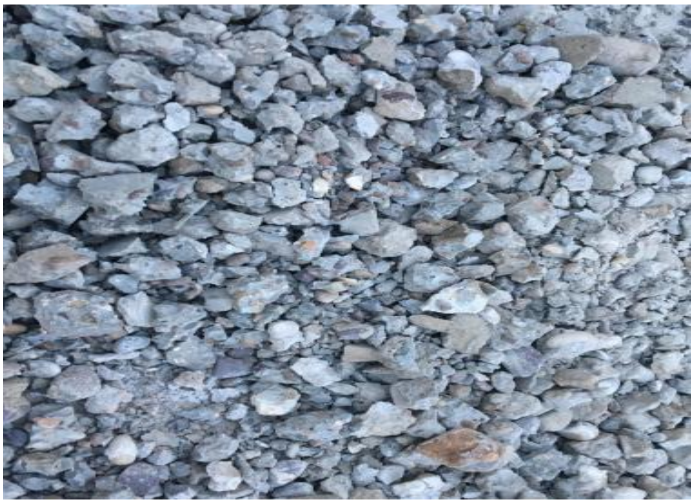


Figure 4. Recycled concrete aggregate used in the experimental study.

Table 3. Grading of coarse aggregate (Natural and Recycled Aggregate).

Sieve Size (mm)	Cumulative Passing (%)		Limitations of IQS
	Natural Aggregate	Recycled Aggregate	
10	100	100	100
4.75	90	94	85-100
2.36	20	25	0-25
1.18	0	0	0-5

6.5 Steel Fibers

Straight and round steel fibers of length=(13mm), diameter=(0.2mm), density =(7800 kg/m^3), modulus of elasticity=(210 GPa) and tensile strength=(2600 MPa) complying with [ASTM A820/A 820M-04] produced by Chinese company (Hebei-Yusen-Metal Wire-Mesh Comp.Ltd) as shown in **Fig. 6** was used. In experimental work, fibers were usually used from (0 up to 2% by volume). The increase in fiber content leads to reduce concrete workability.

6.6 Steel Reinforcement

All specimens were reinforced with four longitudinal deformed steel bars (with 4-φ10 mm). Ties were made of 4mm bar diameter and spaced at 75mm in all the specimens, and the transparent cover was 6mm. **Table 4** shows the properties of the steel bars used.

Table 4. Properties of steel reinforcement.

Bar size (mm)	A (mm^2)	f_y (MPa)	f_u (MPa)	E_s (GPa)
4	12.56	517	601	200
10	78.5	611	725	200

6.7 Superplasticizer

The brand of the superplasticizer employed in this study is GLENIUM-51. Such a brand is chlorides free and complies with types A and F of the ASTM C494-05. Furthermore, this brand worked well with all type of cement and mentioned by international standard.

7. MIX PROPERTIES

Concrete mixture was made with mix proportion (1: 1.44: 2.22) with the ratio of w/c (0.4) and the aggregate in the case of the saturated dry surface when weighed and mixed with cement and water. It is used to produce concrete with 0, 10, 20, 30, 40, 50% replacement of recycled aggregate. The concrete is prepared to find out the compressive strength and the tensile splitting strength.

8. MECHANICAL PROPERTIES OF HARDENED CONCRETE

Table 5 shows the effect of using recycled aggregate on the hardening properties of concrete mixes used in the experimental part for the present research. Each mix type was tested for cylinders to find compression strength and comparison with control mix (does not contain recycled aggregate).

Table 5. Effect of the percentage of recycled aggregate on properties of hardened concrete.

Columns Designation	Gravel (kg/m^3)		Recycled aggregate %	f'c (MPa)	Percentage (%)***	f_t ** (MPa)	Percentage (%)***
	Natural	Recycled					
C1	1000	0	0	30	0.0	3.8	0.0
C2	900	100	10	32.5	+8.3	4.2	+10.5
C3	800	200	20	34.8	+16.0	4.5	+18.4
C4	700	300	30	29	-3.3	3.61	-5.0
C5	600	400	40	26.7	-11.0	3.2	-15.8
C6	500	500	50	23.4	-22.0	2.9	-23.7

* Cement=450 kg/m^3, Sand=650 kg/m^3, W/C=0.4, and Steel fiber (%)=0 (for all specimens).
**Split tensile strength.
***(+) Increase and (-) Decrease.

Table 6 shows the effect of percentage of steel fiber on the hardening properties of concrete mixes. Three mix type was listed in the table and comparison with control mix C4 (does not contain steel fiber and with 30% recycled aggregate).

Table 6. Effect of steel fiber on Properties of hardened concrete and percentage.

Columns Designation	Fiber %	f'c (MPa)	Percentage (%) ***	f_t ** (MPa)	Percentage (%) ***
C4	0	29	0	3.61	0
C7	1	33	+13.8	4.3	+19.1
C8	2	37	+27.6	4.7	+30.2

* Cement=450 kg/m^3, Sand=650 kg/m^3, W/C=0.4, Natural Gravel=700 kg/m^3 and Recycled aggregate (%)=30 (for all specimens).
**Split tensile strength.
***(+) Increase and (-) Decrease.

9. COMPRESSIVE STRENGTH

Eighteen cubes were subjected to compressive strength test according to **BS 1881-116**, among these 18 cubes, three cubes were "control" cubes with 0% RA. Another three cubes for each mix type is compared with control results as shown in **Fig. 5** to find the effects of recycled aggregate on the concrete mix. **Fig. 6** shows that the effect of steel fiber percentage on the compressive strength of mixes that contain recycled aggregate with a percentage of (30, and 40%).

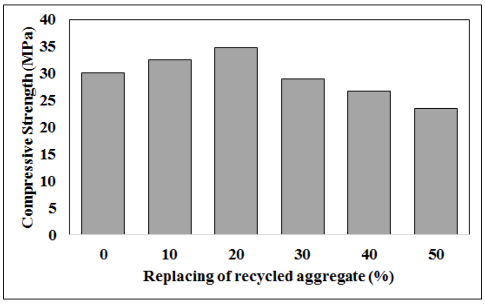


Figure 5. Effect of recycled aggregate on compressive strength (cylinder).

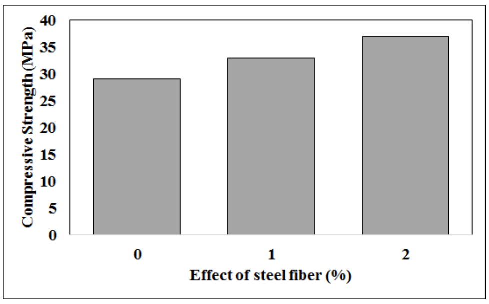


Figure 6. Effect of steel fiber on compressive strength (cylinder)

10. SPLITTING TENSILE STRENGTH TEST

Figs. 7 and **8** show the effect of recycled aggregate and steel fiber on splitting tensile strength respectively. The indirect tensile test (split) according to **ASTM C496-04**.

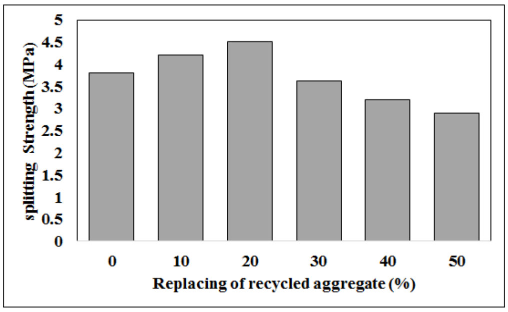


Figure 7. Effect of crushed aggregate on splitting tensile strength.

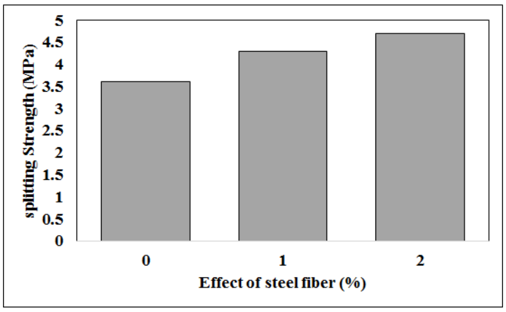


Figure 8. Effect of steel fiber on splitting tensile strength.

11. TESTING PROCEDURE

Reinforced concrete columns casting from of all types of concrete mixtures were examined in a loading device with a capacity of (2000 kN). Before starting the examination, there are some procedures to be taken. First, removing the specimens from the treatment containers and then waiting for drying. Then cleaning it with the brush and exposing it to the white painting for easy examination and drawing the cracks and to be photographed before and after the start of the investigation. Then preparing all the requirements for each test. The column is loaded and placed on the loading device vertically. Before the beginning of the loading process, pieces of rubber were placed on the top and bottom of the model to ensure that the concrete is not crushed. After that, the forces were applied to the column in small divided steps to ensure that the column does not fail from the beginning and that these loads should be placed vertically and centrally. At the start of the test and operation of the device, the device was connected to an external electronic computer to record all loads and axial deformation to give full calculations and sufficient to draw the load-deflection curve. During the loading process and the appearance of cracks on the surface of the concrete, the column must be marked, this marked shows reading loads and cracks on the concrete surface of the column. Loading is continued until the column fails where the device stops recording.

12. MODE OF FAILURE

Photographs of the tested columns with the mode of failure and crack pattern before and after testing are shown in **Fig. 9**. The cracks were generated in the concrete when the tensile stress reaches its strength limit. At the testing time, for the non-fibrous concrete, most of the column specimens produced very similar behavior at early loading stages and the column deformations produced were initially at the elastic zone, and then the applied load was increased until the first crack occurred. As the load increased further, cracks developed and they increased in depth. At the final loading stage, the concrete cover at compression side was crushing and spalling, and the specimens were buckled to the outside, and at the end, the column failed by yielding of longitudinal steel reinforcement. For fibrous concrete column this behavior is not noticed, where the steel fiber is the primary factor that affects the appearance of cracks in concrete and changed the mode of failure from brittle to ductile. Increasing steel fiber generated more strength columns with higher ultimate loads and lesser deformation and with improvements in ductility and toughness. The contribution of fiber and their excellent orientation and distribution in the mixture prevents the appearance of a crack and reduces the tensile stress at the cracks zone which restricted the cracking propagation.

Figure 9. Crack pattern and mode of failure columns.

In all the samples of the columns examined, there is no apparent effect of recycled aggregate on the failure modes for all stages of aggregate replacement, while there is a significant effect on the failure modes when the percentage of steel fiber is used in the reinforced concrete mix.

13. ULTIMATE CAPACITY AND LOAD-DISPLACEMENT

Ultimate load and axial deflection of the columns are listed in **Table 12**. This table shows the influence of the load carrying capacity of columns varies over the various types of concrete mix which that depends on recycled aggregate replacement and percentage of steel fiber added to the concrete mixes. For the reinforced concrete columns (C2 and C3), the replacement of (10 and 20%) of recycled aggregate causes an increase in the ultimate load of about (7.2% and 11.2%). Also, for the reinforced concrete columns (C4, C5, and C6), the replacement of (30, 40 and 50%) of recycled aggregate, causes a decreasing in the ultimate load of about (2.7%, 8.8% and 18.3%), respectively,

As expected, when steel fiber added with a constant ratio of replacement of recycled aggregate (30%), the failure load was indicating a significant enhancement in the ultimate capacity. It has been observed that the ultimate load capacity of reinforced concrete columns (C7 and C8) with steel fiber (1% and 2%) is more than that of reinforced concrete columns without steel fibers (C4), the percentage increase in the ultimate load capacity are (12.0% and 24.5%) respectively, as shown in **Table 7**.

Table 7. Effect of recycled aggregate and steel fiber ratio on the load and deflection readings.

Column Designation	Fiber (%)	Recycled Aggregate (%)	Ultimate load (kN)	Percentage in ultimate load (%)	Axial deform. (mm)
C1	0	0	180	0	8.0
C2	0	10	193	7	8.6
C3	0	20	202	11.2	9.0
C4	0	30	175	-2.7	7.8
C5	0	40	164	-8.8	7.3
C6	0	50	147	-18.3	6.6
C7	1	30	196	12	8.7
C8	2	30	218	25	9.7

The load-deflection curves that obtained from the experimental study are plotted to compare with the results obtained from the analytical study by using the ANSYS program, as shown in **Figs. 19** through **Fig. 28**.

14. MODULUS OF ELASTICITY

In order to obtain the data for ANSYS that help to do theoretical study to recognized between all types of concrete mix then approached to correct representation for regular concrete, recycled and steel fiber concrete, measurements of static modulus of elasticity of concrete (E_c) for all types of mix was carried out in accordance with **ASTM C-469**. As shown in **Table 8**, (300x150 mm) concrete cylinders were tested in compression at constant strain as shown in **Fig. 10**.

Table 8. Test results of modulus of elasticity.

Mix designation	Modulus of elasticity (MPa)
C1	27650
C2	27830
C3	27850
C4	26250
C5	25130
C6	24450
C7	29430
C8	30250

Figure 10. Modulus of elasticity test.

15. NON-LINEAR FINITE ELEMENT MODELS

The non-linear finite element analysis was transported to investigate the behavior of the reinforced concrete columns using the ANSYS software. The investigated behavior includes the crack pattern, the maximum load and the load and deflection response of the columns tested in the laboratory. An acceptable concordance was found between the experimental tests conclusions and the finite element program.

16. GEOMETRY MODELING

In this study, eight columns were analyzed by ANSYS (Released 16.1) programs to make verification study with the dimensions and properties corresponding to the actual experimental data. The specimen will be modeled using eight-node three-dimensional concrete solid element (SOLID65) and (link8) element was used to model the steel reinforcement, with two nodes to represents the link element, with 3 degrees of freedom and translations in x, y, and z directions. The comparison shows that the ANSYS nonlinear finite element program is capable of modeling and predicting the actual nonlinear behavior of columns with having different characteristics.

17. MATERIAL PROPERTIES

To represent the differences in materials in the program, a stress-strain diagram must be introduced. Concrete has two stress-strain drawing depending on the behavior of concrete in compression and tension. The concrete stress-strain concluded from experimental work of cylinders in the compression state test. Division of the curve into multiple points with x and y coordinate data to represent the curve through the program must be applied from the beginning of the curve through the ultimate compressive strength till the crushing on concrete as shown in **Fig. 11**. The small division must be performed to represent the whole curve.

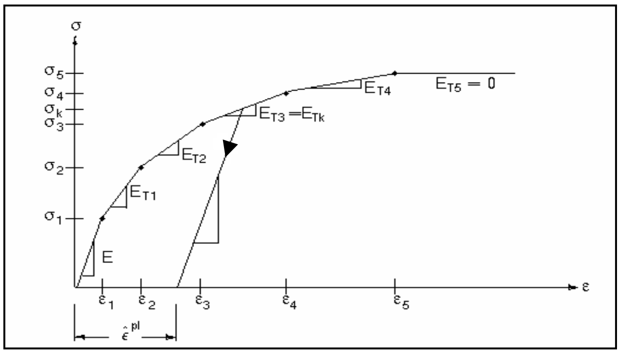
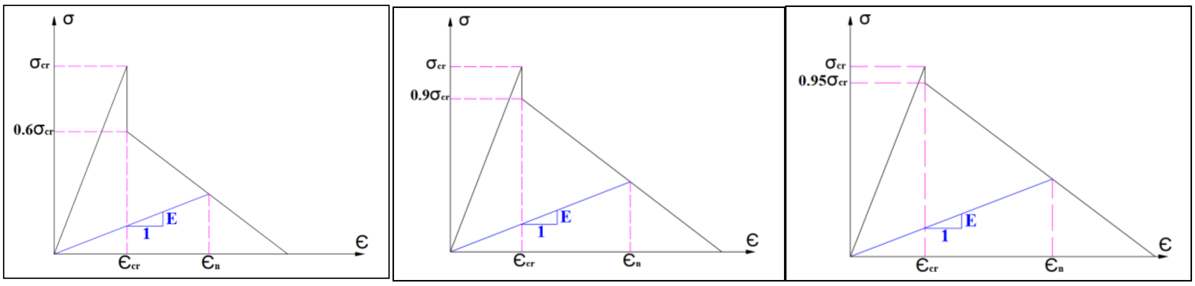


Figure 11. Multilinear stress-strain curve for concrete adopted in the analysis, **ANSYS help**.

18. BEHAVIOR OF CONCRETE IN TESTING (BEHAVIOR OF STEEL FIBER REINFORCED CONCRETE)

Concrete is simulated in tension by (tensile-stress-strain diagram), which can be presented and explained before cracking by linear elastic model. Generally, after concrete cracking; cracking could be presented by principal tensile stresses or strain which related to the beginnings of cracks appearance. To represent the tensile behavior, the theoretical work presented two methods of the tension-stiffening model which are defined as suitable for analyzing reinforced concrete sections without fibers and suitable for analyzing fiber reinforced concrete sections. It can produce theoretical load-deflection response close to experimental one, and the ultimate loads are close to the actual experimental failure loads, as shown in **Fig. 12**, the reason for using tension-stiffing model and no other model because of concrete during cracking still holding a tensile stresses perpendicular to the cracks itself.



(a) (b) (c)

Figure 12. Post-cracking model of (a) normal reinforced concrete (b) steel fiber reinforced concrete [vf=1%] (c) steel fiber reinforced concrete [vf=2%].

19. ELEMENT MESHING, LOADS AND BOUNDARY CONDITIONS

After collecting all the data required to be entered into the program in terms of physical properties and engineering division and the size, dimensions, and areas of reinforcing steel and concrete, the desired shape was initially inserted by applying it to the program and then get a whole general shape to be then divided into small elements into cubes to give and simulate the original shape of the column, which was examined by a practical examination. All the data entered into the program correctly makes the program work and simulates the column theoretically in terms of the loads that can be applied to the column. Before the implementation of the analysis by the program, some requirements must be met to ensure that the model works, these are the locations of loading and places of support where all movement in the bottom of the column held to zero ($\delta x=0$, $\delta z=0$, and $\delta y=0$). The movement of the column was stopped to parallel the non-movement of the device and the installation of the model. From the top, loads were placed, similar to loads carried from the device, but was divided and distributed on the nodes to represent the central axial pressure. Before running the program, the loads are divided into steps to prevent the failure of the model and theoretically assume these loads according to the Newton- Raphson procedure. The program runs to analyze and draw relationships, which is the ultimate load. Then the program stopped, and the highest failure load was concluded. The solution is stopped for compatibility between the theoretical and practical solution. Failure of the theoretical model can be determined when the solution for minimum load steps cannot be converging.

20. FINITE ELEMENT RESULTS

Fig. 13 to **Fig. 20** below show the comparison between the ultimate load-deflection curve of the experimentally tested column and finite element program. The theoretical work is applied to verify that the finite element programs can examine many structural elements. The programs able to show the ultimate failure loads, cracking loads, deformations, mode of failure and stresses contour diagram, all these parameters work as ensuring factors for the accuracy of the finite element models compared to the experimental results. In the present investigation, the predicted load-deflection curve obtained is compatible with experimental load-deflection curve from the beginning of loading through cracking load finally till the ultimate load. After cracking load, a slight differences response is presented. At the final loading stage yielding of steel reinforcement followed by concrete, crushing is the failure type of column presented in this numerical research. It was concluded that the general behavior of the finite element models shows a proved compatibility with the experimental tests results between (89% to 95%). From the stresses contour, the plot shows that the concentration of higher axial stress presented within the center region of the cross-section for the column. **Fig. 21** show differences in ultimate load between all reinforced concrete columns which are tested experimentally, while **Fig. 22** show differences in ultimate load between all reinforced concrete columns which are analyzed in ANSYS software. Stresses contour of the finite element of the analyzed column C3 is shown in **Fig. 23**.

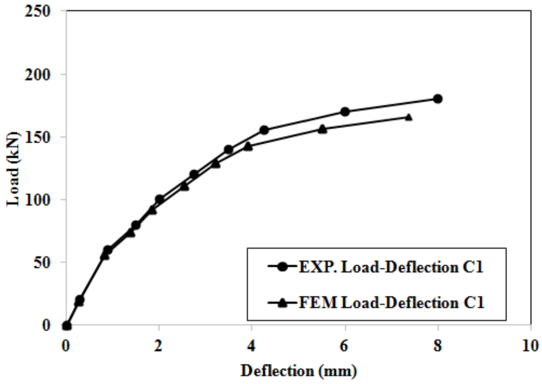


Figure 13. Comparison between EXP. and ANSYS load-deflection curve for column 1.

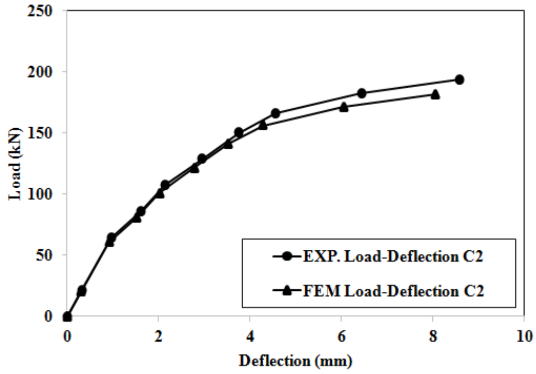


Figure 14. Comparison between EXP. and ANSYS load-deflection curve for column 2.

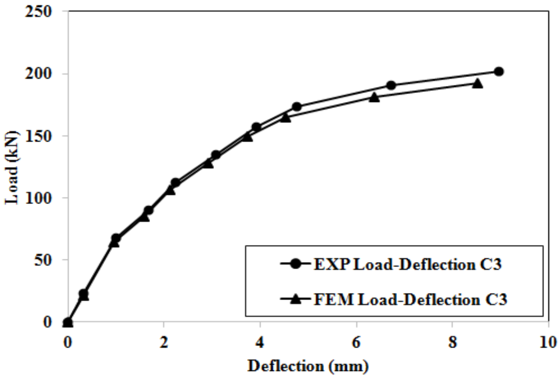


Figure 15. Comparison between EXP. and ANSYS load-deflection curve for column 3.

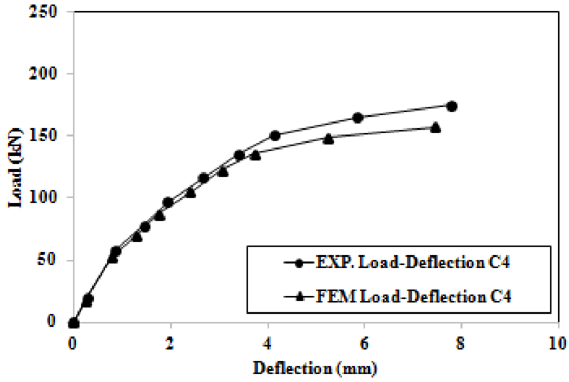


Figure 16. Comparison between EXP. and ANSYS load-deflection curve for column 4.

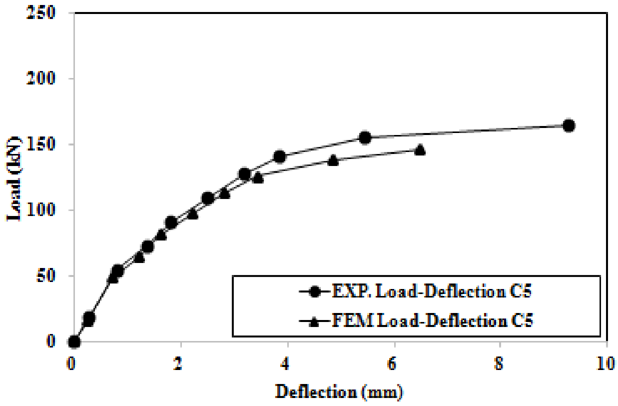


Figure 17. Comparison between EXP. and ANSYS load-deflection curve for column 5.

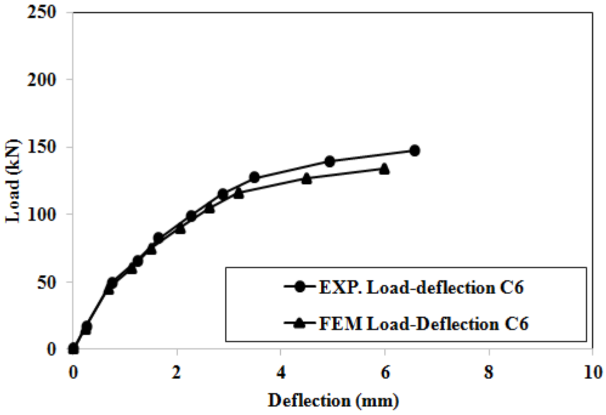


Figure 18. Comparison between EXP. and ANSYS load-deflection curve for column 6.

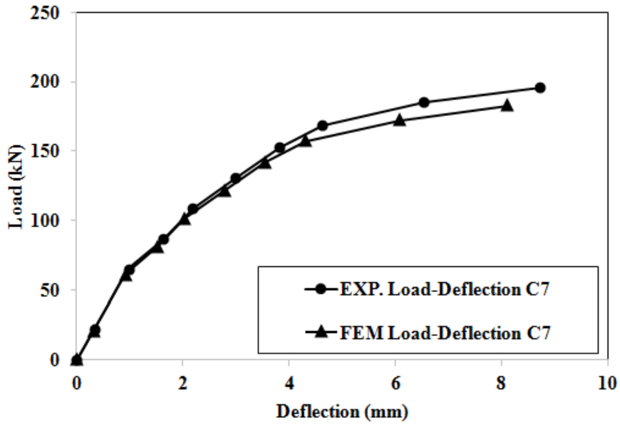


Figure 19. Comparison between EXP. and ANSYS load-deflection curve for column 7.

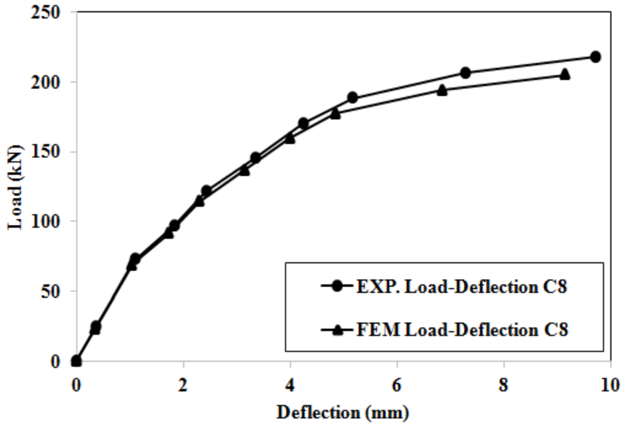


Figure 20. Comparison between EXP. and ANSYS load-deflection curve for column 8.

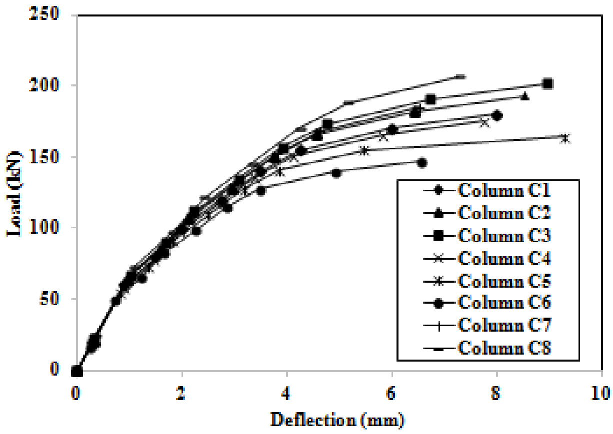


Figure 21. Comparison between Exp. Load-deflection curve for all column tested.

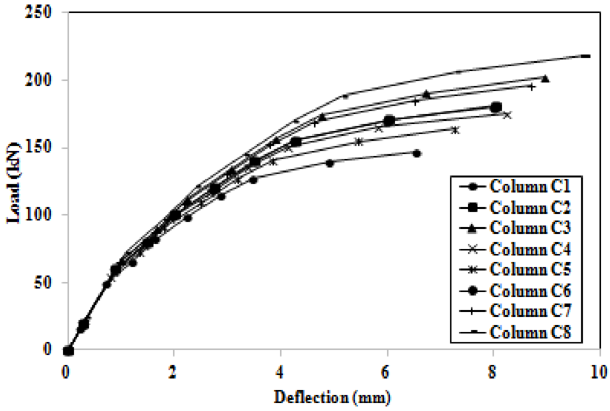


Figure 22. Comparison between Load-deflection curve for all column analyzed.

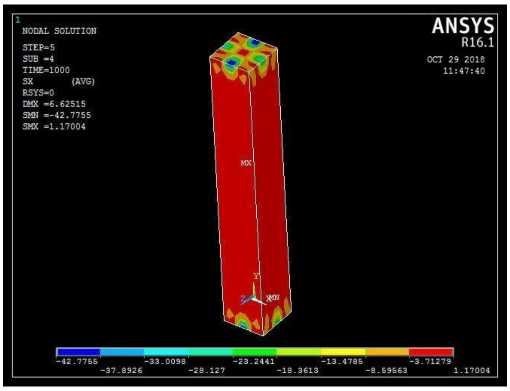


Figure 23. Variation in concrete stress along the column C3.

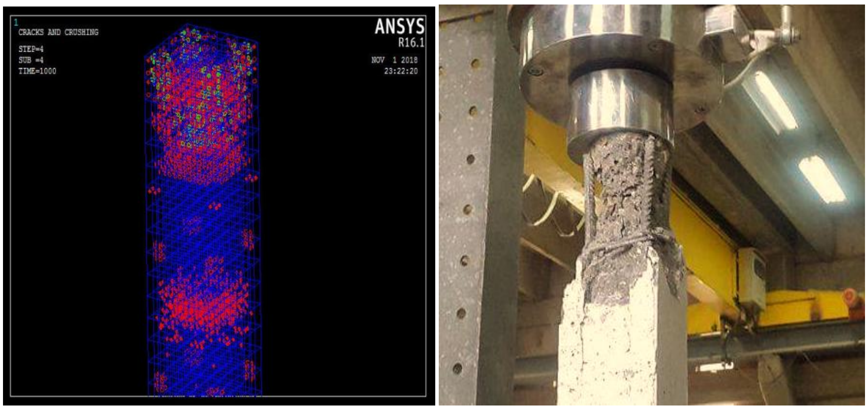
Table 9 reveals the comparison between all columns which are tested in the laboratory then which are analyzed in finite element Technique using the ANSYS program (version 16.1).

Table 9. Comparison between experimental ultimate load and ANSYS.

Column designation	Ultimate load (kN)	FEM. load (kN)	FEM/EXP
C1	180	166	0.92
C2	193	181	0.94
C3	202	192	0.95
C4	175	158	0.90
C5	164	146	0.89
C6	147	134	0.91
C7	196	182	0.93
C8	218	205	0.94

21. CRACK PATTERNS

In ANSYS computer program, the crack pattern at ultimate load for columns can be presented. The crack patterns obtained from the finite element analysis and failure modes of the experimental beams agree well, as shown in **Fig. 24** for column C1. **Fig. 25** shows the analytical cracking for columns C3 and C7 at ultimate load.



a. Numerical crack pattern b. Experimental crack pattern.

Figure 24. Numerical and experimental cracking patterns of column C1.

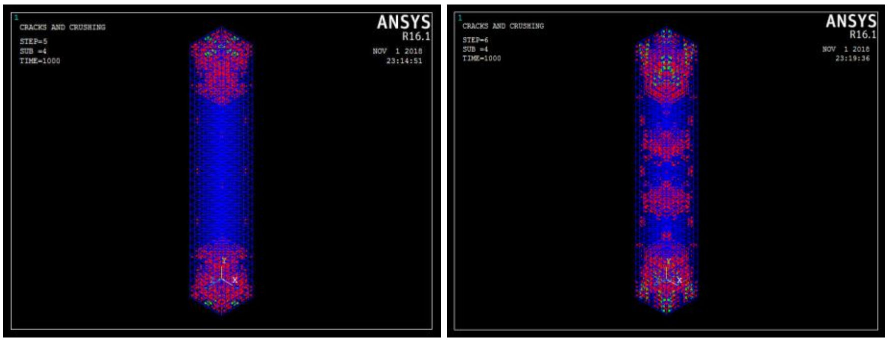


Figure 25. Numerical cracking patterns of columns C3 and C7.

22. Stresses in Steel Reinforcement

The determination of the stress distribution along the steel bars is a costly approach in the experimental program. However, the strain gauges can be replaced by virtual strain (and stress) gauges represented by the numerical results using the finite element analysis (by ANSYS software). Thus, it is one of the ways where the benefit of using the finite element analysis as an "analytical test machine" is clearly evident. **Fig. 26** shows predicted longitudinal stress distribution at longitudinal steel bar for column C3 at ultimate load using finite element method.

Figure 26. Longitudinal steel bar stress distribution for column C3 at ultimate load.

It can be noted that for the main bars of column C3, the stress levels increases and reaches the maximum after 6 cm from the top and bottom of the column. All stresses data (main and stirrups reinforcements) that register by finite element analysis not reached the yielding point.

23. CONCLUSIONS

- During casting as the proportion of recycled aggregate increases, workability decreases.
- Replacement of a 20% of virgin coarse aggregate led to an improvement in concrete characteristics strength much higher than when another coarse percentage aggregate was replaced by recycled aggregate.
- The ultimate load capacity of recycled aggregate concrete columns with 10% and 20% replacement was increased of 7.2% and 12.2% respectively, as compared with the natural aggregate concrete column.
- The ultimate load capacity of recycled aggregate concrete columns with 30%, 40%, and 50% replacement was decreased of 2.8%, 9.7% and 22.4% respectively, as compared with the natural aggregate concrete column.
- Compressive strength for recycled aggregate concrete was increased when recycled aggregate was being used instead of virgin coarse aggregate a replacement of (10% and 20%) led to an increase in compressive strength of (8.3% and 16.0%) respectively.
- Splitting Tensile Strength for recycled aggregate concrete were increased when recycled aggregate was being used instead of virgin coarse aggregate a replacement of (10% and 20%) led to an increase in tensile strength of (10.5% and 18.4%) respectively.
- Compressive strength for recycled aggregate concrete was decreased when recycled aggregate was being used instead of virgin coarse aggregate a replacement of (30%, 40%, and 50%) led to a decrease in compressive strength of (3.4%, 12.3%, and 28.2%) respectively.
- Splitting Tensile Strength for recycled aggregate concrete were decreased when recycled aggregate was being used instead of virgin coarse aggregate a replacement of (30%, 40%, and 50%) led to a decrease in tensile strength of (5.2%, 18.7%, and 31.0%) respectively.
- Increasing of fiber from (0 to 1 and 2%) causes an increase in ultimate load capacity of reinforced concrete columns about (0, 12.0 and 24.5%) for recycled aggregate concrete with 30% aggregate replacement.

- Increasing of fiber from (0 to 1 and 2%) cause an increase in compressive strength of about (0, 13.8 and 27.8%) for recycled aggregate concrete with 30% aggregate replacement.
- Increasing of fiber from (0 to 1 and 2%) cause an increase in splitting tensile strength of about (0, 19.1 and 30.2%) for recycled aggregate concrete with 30% aggregate replacement.
- Fibers reduce the width of the crack by reducing the stresses concentrations.
- Increasing of fiber from (0 to 1 and 2%) cause an increase in modulus of elasticity of about (0, 12.1 and 15.2%) for recycled aggregate concrete with 30% aggregate replacement.
- The compatibility between the experimental tests results and theoretical analysis are between (89% to 95%).
- It is recommended that 20% of recycled aggregate is used.
- The use of superplasticizer for strength and workability suitable for concrete, in this (recycled aggregate concrete), mainly when steel fiber in the concrete mix was used.
- There is no effect on failure patterns when natural aggregate is replaced.

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