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EFFECT OF EXPOSURE TO FIRE ON THE BEHAVIOR OF RECYCLED AGGREGATE CONCRETE BEAM WITH OR WITHOUT REUSED STEEL REINFORCEMENT

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ABSTRACT

To examine the effects of elevated temperature on recycled aggregate concrete as well as recycled aggregate concrete beams made using new and reused steel reinforcement, four concrete mixes with different recycled aggregate replacement ratios (0%, 25%, 50%, 75%) and two types of steel reinforcement (new steel and reused steel reinforcement) were used to cast the beams. Twenty- four cubes and twenty-four beams were tested using a compressive strength test and four-point load test, half of them made with new steel reinforcement and the other half using reused-steel steel reinforcement. Twenty-two beams were subjected to an elevated temperature of (400) °C for (3) hours, while two beams were kept as control beams. While half of the cubes were subjected to an elevated temperature of (400) °C for (3) hours and the others were tested at normal room temperature. It was observed that replacing natural aggregate with recycled aggregate by (25%, 50% &75%) decreased the compressive strength by (8.04%, 16.39%, and 27.9%) respectively without being subjected to elevated temperature and by (4.07%, 20.36%, and 33.31%) respectively after been subjected to elevated temperature. New steel reinforcement beams made of (25%, 50%, and 75%) recycled aggregate had lower ultimate strength by (3.75%, 10.12%, and 27.08%) respectively compared to fully natural aggregate new steel reinforcing beams all subjected to elevated temperature. On the other hand, reused-steel reinforcement beams had lower ultimate strength by (14.25%, 34.76%, and 40.89%) respectively compared to natural aggregate reused-steel reinforcing beams all subjected to elevated temperature.

Keywords: recycled aggregate concrete1, reused steel reinforcement.

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1. INTRODUCTION

In the last few decades, high population growth rates led to an increase in construction development and the demand for infrastructure; this increased the consumption of steel reinforcement, concrete, and many other non-renewable materials.

More than 26.8 billion tons per year was the global aggregate demand in 2011 (Fredonia 2007), furthermore, the amount of solid waste produced from construction and demolished waste is estimated to be 900 million tons per year in Europe, the USA, and Japan (World Business Council for Sustainable Development (WBCSD).

Recycling is the best method to decrease the consumption of non-renewable resources and to dispose of solid waste. One of the recycling methods of concrete is to transform it into recycled aggregates (RA) by crushing, then the RA is used in the production of new concrete, which is not a new concept in the construction industry, as the properties of RA were studied by Gluzhge in 1946.

Many studies investigated the effect of RA on the behavior of concrete; it was observed that the RA contains micro cracks as well as the old mortar that covers the RA causing a decrease in the bond with the new mortar these lead to a decrease in the concrete strength, [3, 13]

Also, Abedalqader *et al*. [3], observed the effect of elevated temperature on RA concrete strength as the temperature evaporates the capillary water found in the RA, this vapor causes pressure on the micro-cracks found in RA leading to a decrease in the concrete strength.

Zou *et al.* [30] studied the bond between steel reinforcement and concrete subjected to elevated temperature and observed that the bond strength decreased as temperature increased regardless of RA content due to the loss of friction between the steel bars and the concrete as the temperature increased. Also, it can be observed that there is no significant difference in the percent loss of strength for different RA content.

Bsisu, K. and Salem, Z. [10], studied the bond between the used steel reinforcement with normal and high strength concrete and concluded that the strength of the bond between concrete and steel depends on the deformations of the steel bar rather than psychical adhesion and all the steel reinforcement should be cleaned before being used in construction.

While the previous research didn't study the behavior of recycled aggregate concrete beams made using reused steel reinforcement and subjected to elevated temperature, this study aims to investigate this behavior and compare it with the behavior of recycled aggregate concrete beams made using new steel reinforcement.

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2. EXPERIMENTAL PROGRAM

2.1 Materials

2.1.1 Steel reinforcement

Two types of steel reinforcement were used in this research,

a) New steel reinforcement: (10) mm diameter deformed bars of grade (60), specified yield stress=420 MPa were used as flexural reinforcement for half of the specimens, and (8) mm diameter deformed bars of grade (40), specified yield stress= 280MPa were used as stirrups for all the specimens.

b) Reused-steel reinforcement: (10) mm reused-steel bars obtained from a local market were used as flexural reinforcement for half of the specimens.

2.1.2 Cement

Ordinary Portland Cement (OPC) type (I) complies with (ASTM C150-02)was used for the concrete mixture

2.1.3 Coarse aggregate

Two types of coarse aggregates were used: 1) natural coarse (crushed limestone) aggregate (NCA) and 2) recycled coarse aggregate (RCA) obtained by crushing concrete test cubes used to check the concrete strength obtained from a local lab.

For both types of coarse aggregate, the maximum aggregate size used was 19 mm.

To ensure that the gradation is consistent with ACI C33 code requirements, all the aggregates were sieved and separated according to the size of the aggregate.

Figure-1 shows the coarse aggregate gradation and Table-1 below shows the properties of the coarse aggregate.

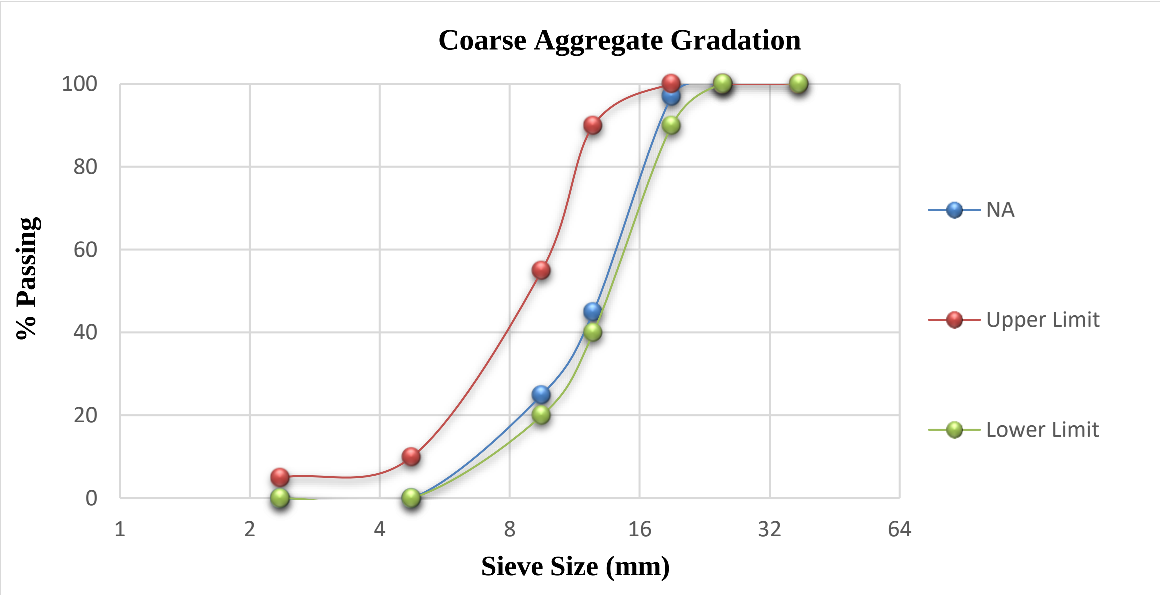

Figure-1. Coarse aggregate gradation.

Table-1. Coarse aggregate properties.

Property	NCA	RCA
Bulk specific gravity (DRY)	2.5	2.33
Bulk specific gravity SSD	2.58	2.44
Absorption (%)	2.57	4.32
Dry rodded unit weight (kg/m^3)	1840	1651

2.1.4 Fine Aggregates

A mix of 75% crushed limestone and 25% silica was used as fine aggregate, and a sieve analysis test was performed on the fine aggregate to ensure that the grading complied with the ASTM C136/C136M. Table-2 shows the properties of the fine aggregate mix.

Table-2. Fine aggregate properties.

Property	NFA	Silica
Bulk specific gravity (DRY)	2.52	2.61
Bulk specific gravity SSD	2.58	2.64
Absorption (%)	2.4	0.5
Dry rodded unit weight (Kg/m3)	1922.53	2010.3

2.2 Mix Design

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Four concrete mixes were designed according to ACI-211 code with average cylindrical strength (fc') equal to (35) MPa. The Four Mixes were divided according to the amount of the recycled aggregate (RAC0, RAC25, RAC50, RAC 75), Table-3 shows the details of mix proportions.

Table-3. Details of mix proportions per $(0.32)m^3$.

RA %	NCA (wet) (kg)	RCA (wet) (kg)	NFA (wet) (kg)	Silica (wet) (kg)	Net Water (kg)	Cement (kg)
0%	372.385	0.000	111.725	38.788	75.697	136.170
25%	279.289	85.435	116.524	40.454	74.987	136.170
50%	186.193	170.870	121.323	42.120	74.276	136.170
75%	93.096	256.305	126.122	43.786	73.565	136.170

2.3 Compressive Strength

For each mix six (150 X 150 X 150 mm) cubes were cast to test the compressive strength, half of the cubes were subjected to the elevated temperature of (400) °C for (3) hours and then tested, and the other half were tested without being subjected to elevated temperature. Table 4 shows the average compressive strength for each mix.

For cubes that were not subjected to elevated temperature, it can be observed that the minimum strength reduction due to recycled aggregate occurred in (25%) RA mix, and as the replacement percent increases the reduction in strength increases, the decrease in the compressive strength due to recycled aggregate is similar to studies [13] as the RA contain micro-cracks makes it weaker than the NA and causing a reduction in the compressive strength. Furthermore, the old mortar that covers the RA weakens the bond between the aggregate and the new cement past, also it weakens the interfacial transition zone causing a reduction in the compressive strength.

While for cubes that were subjected to elevated temperature, it can be concluded that the RA replacement percentage that has the lower effect on the compressive strength is (25%) and the strength of this replacement percentage can be enhanced by using a mix design for higher strength than the required one.

Also, it can be observed that the temperature causes a decrease in the compressive strength for the same RA% and this reduction increased as the RA% increased, which complies with similar studies [3], this reduction occurs because the temperature evaporates the capillary water producing pressure on the micro-cracks found in the recycled aggregate. Also, it weakens the interfacial transition zone leading to a reduction in the compressive strength of the concrete.

Table-4. Cubes compressive strength.

RA %	average fc`(MPa) at Temp (25)°C	% Reduction due to recycled aggregate at Temp (25)°C	average fc`(MPa) at Temp (400)°C	% reduction due to elevated Temp.	% reduction due to recycled aggregate at Temp (400)°C	% reduction due to recycled aggregate and elevated Temp.
0%	35.37	-	30.55	13.61%	-	-
25%	32.52	8.04%	29.31	9.87%	4.07%	17.12%
50%	29.57	16.39%	24.33	17.71%	20.36%	31.20%
75%	25.47	27.9%	20.38	20%	33.31%	42.39%

2.4 Tested Specimens

For this research twenty-four beams (0.2x0.2x1.10) m were cast, six beams for each concrete mix, half of the beams were made using new ϕ10 steel reinforcement as flexural steel, while the others were made using reused-steel reinforcement as flexural steel and the stirrups for all the beams were ϕ8 new steel reinforcement, Figure-2 shows the detailed steel reinforcement of the beams.

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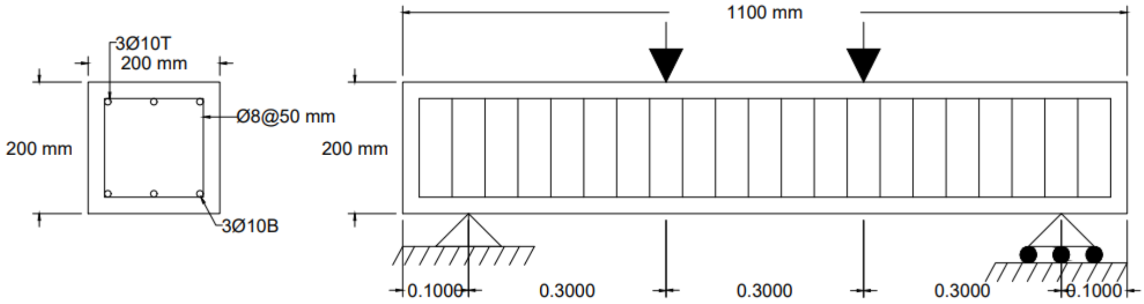

Figure-2. Beams steel reinforcement.

2.5 Test Setup

2.5.1 Heating and testing process

An electrical furnace available at the structural laboratory of Jordan University of Science and Technology was used to expose the beams and cubes to the elevated temperature of (400)°C for (3) hours, Figure-3 shows the electric furnace.

After exposing the specimens to the elevated temperature, a four-point load test was done on the specimens, and a linear variable differential transformer was used to monitor the beams' deflection Figure-4 shows the four-point load test setup.

The specimens were divided into categories depending on the recycled aggregate replacement ratio (0%, 25%, 50%, and 75%). All the specimens were exposed to the elevated temperature except two beams with (0%) replacement ratio were used as control specimens.

Figure-3. Electrical furnace.

Figure-4. Four-point load test.

3. RESULTS AND DISCUSSIONS

3.1 Loads and Failure Modes

The experimental failure loads, ultimate deflections, and the failure modes for all the beams are presented. Table-5 and Figure-5 show the load-deflection curves for all the beams.

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Table-5. Ultimate deflections and failure modes.

Sample Name	Ultimate Load (KN)	Ultimate Deflection (mm)	Failure Mode	Sample Name	Ultimate Load (KN)	Ultimate Deflection (mm)	Failure Mode
NCB	170.12	9.01	Flexural	UCB	148.70	13.27	Flexural
N0R1	162.88	12.11	Flexural	U0R1	138.40	13.17	Flexural
N0R2	161.75	10.06	Flexural	U0R2	132.60	16.77	Flexural
AVG	162.32	11.08		AVG	139.90	14.40	
N25R1	163.10	17.13	Flexural	U25R1	131.60	16.77	Flexural
N25R2	146.00	15.15	Flexural	U25R2	116.40	16.48	Flexural
N25R3	159.60	16.17	Flexural	U25R3	111.90	17.34	Flexural
AVG	156.23	16.15		AVG	119.97	16.86	
N50R1	140.00	15.81	Shear	U50R1	93.90	6.06	Shear
N50R2	147.00	15.58	Shear	U50R2	87.30	6.27	Shear
N50R3	150.65	12.61	Shear	U50R3	92.60	6.62	Shear
AVG	145.88	14.67		AVG	91.27	6.32	
N75R1	117.30	5.98	Shear	U75R2			
N75R2	120.20	7.39	Shear	U75R2	83.50	17.16	Shear
N75R3	117.58	8.32	Shear	U75R1	81.90	12.86	Shear
AVG	118.36	7.23		AVG	82.70	15.01	

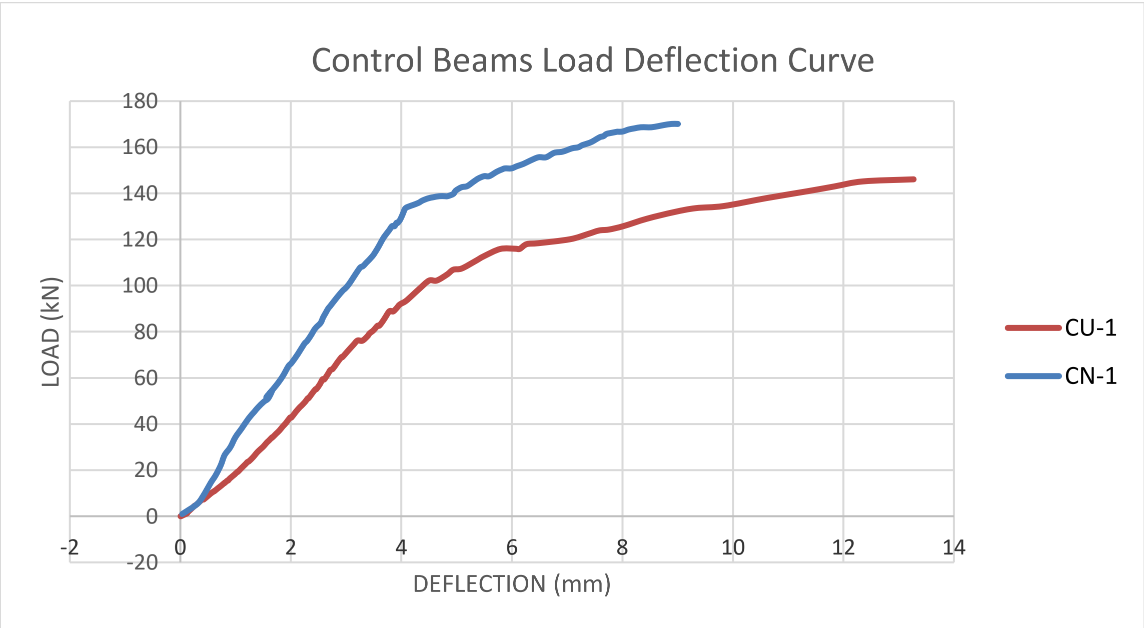

Figure-5. Control beams load deflection curve.

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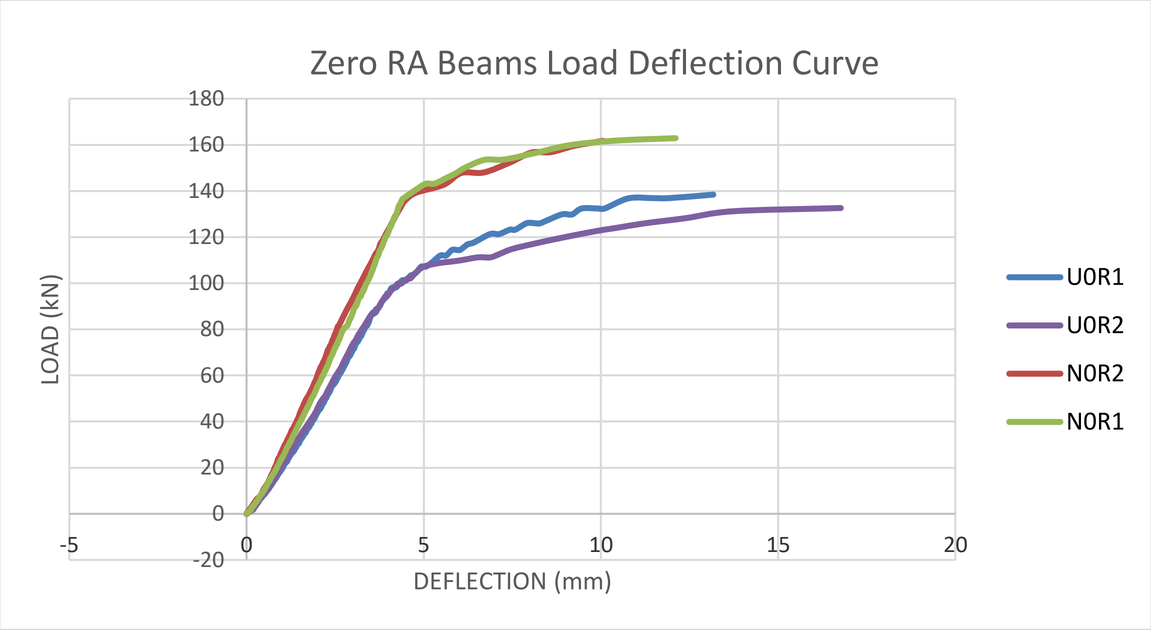

Figure-6. Zero RA beams load deflection curve.

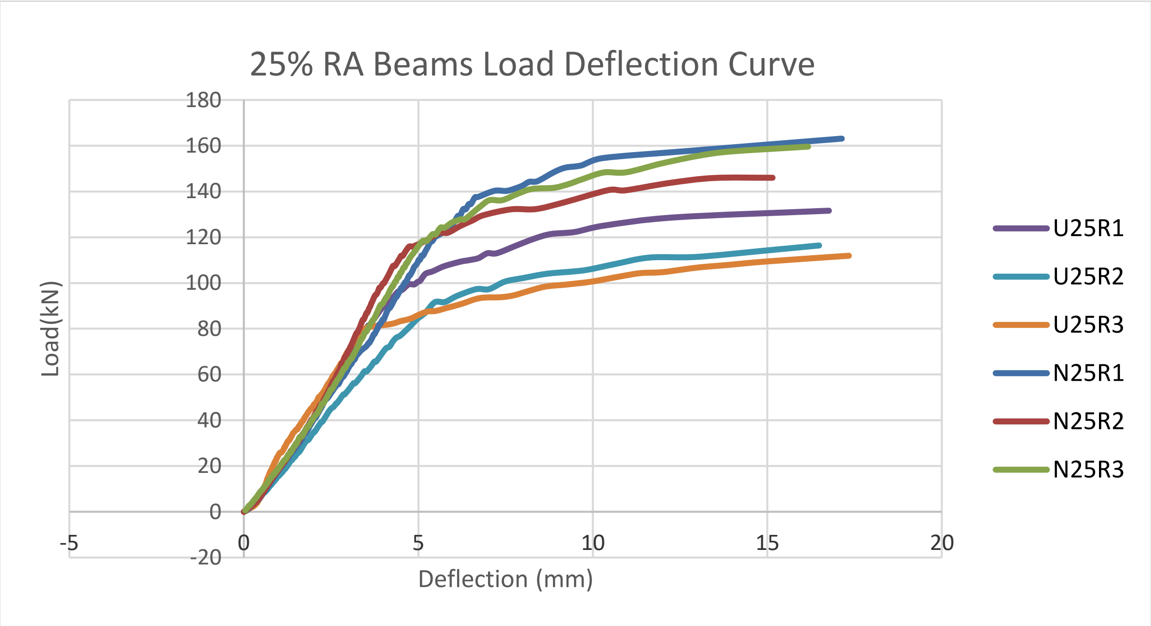

Figure-7. 25% RA beams load deflection curve.

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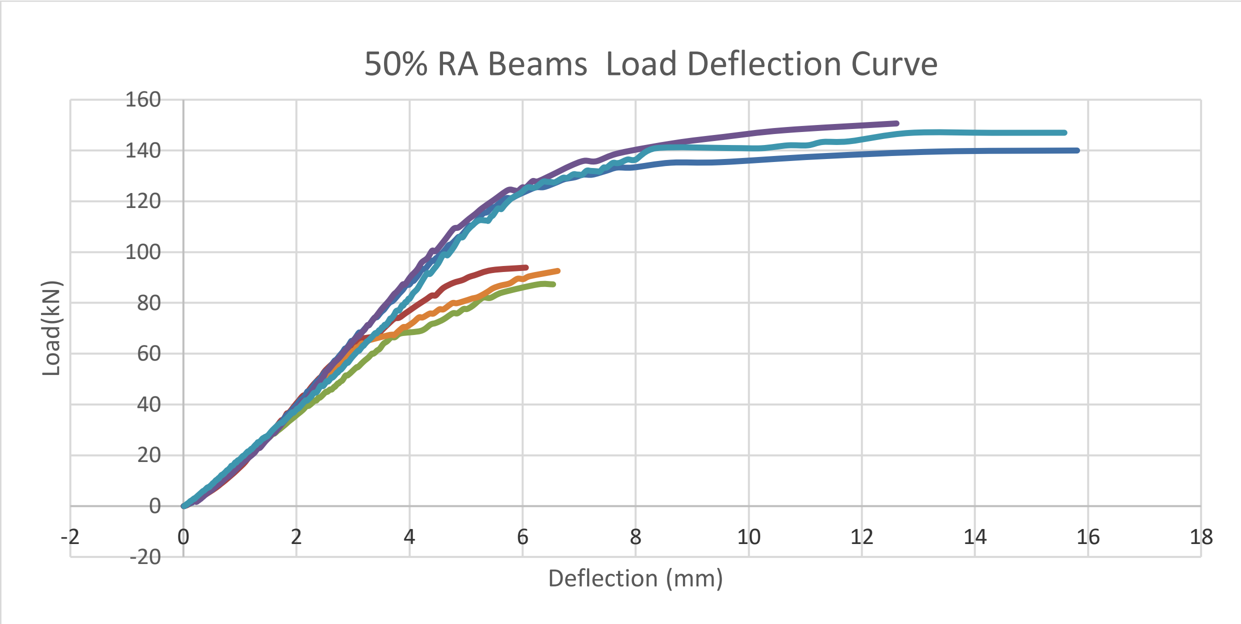

Figure-8. 50% RA beams load deflection curve.

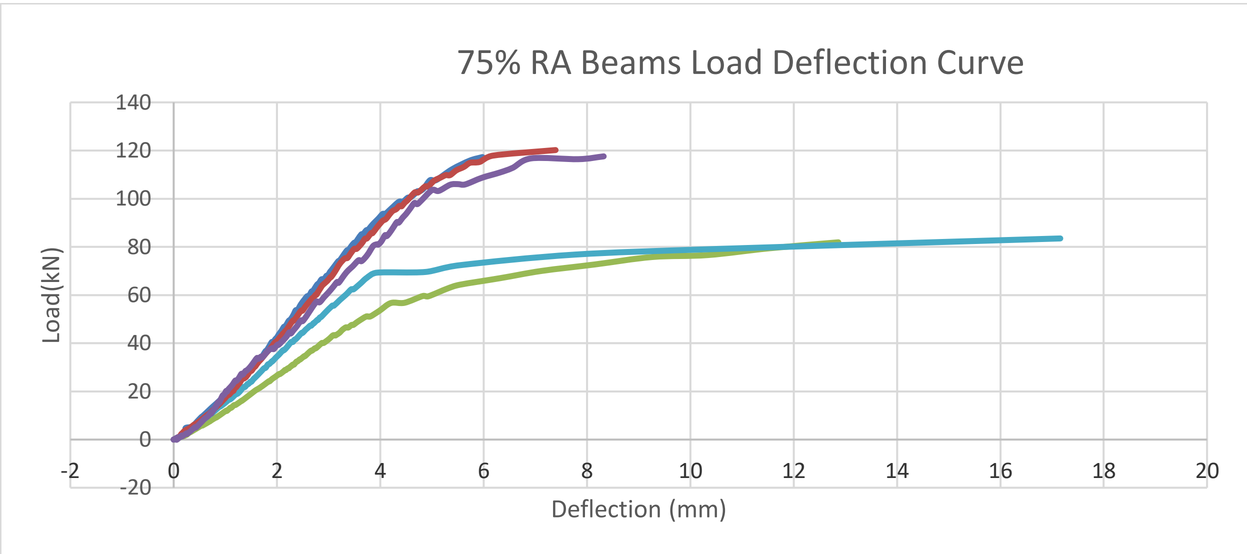

Figure-9. 75% RA beams load deflection curve.

3.2 Effect of recycled aggregate and elevated temperature on the mode of failure for all the beams

According to ACI 318-14 code, it states that if the distance between the support and the load is less than (2h) then the beam is a deep beam, using ACI 318-14 equations and deep beam design research [23] the flexural capacity and nominal shear capacity are 121 kN, 120 kN respectively for the control beam made using new steel reinforcement.

Researchers [8, 13, and 18] concluded that the increase in the recycled aggregate in the concrete mix causes a decrease in the shear strength of the concrete.

So, it can be concluded that the change from flexural failure to shear failure for (50% and 75%) of recycled aggregate concrete is due to two main reasons:-

a) The flexural capacity and the shear capacity are very close to each other.

b) The decrease in the shear capacity due to the recycled aggregate, according to the existing research, causes the shear capacity to be lower than the flexural capacity leading to shear failure.

3.3 Effect of recycled aggregate and elevated temperature on new steel reinforcement beams

- Fully natural aggregate beams

The elevated temperature led to a decrease in the ultimate strength of the beams by (4.58%) as the elevated temperature caused a reduction in the compressive strength.

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The cross-sectional area and the moment of inertia of the beam didn't change so the increase in the ultimate deflection by (8.68%) was due to the reduction that occurred in the beam modulus of elasticity.

- (25%) replacement ratio

The beams had a lower ultimate failure load compared to (0%) RA beams subjected to elevated temperature, by (3.75 %,). However, the ultimate deflection increased by (45.75%), this happened due to the reduction occurred in the beam modulus of elasticity.

- (50%) replacement ratio

The mode of failure of the beams changed from flexural failure to shear failure, and this is due to the reasons discussed above. However, there was an increase in the deflection of the beams compared to (0%) RA beam and it can be observed that the beams were going towards flexural failure, but at the end, the mode of failure was a shear failure.

Also, the change in the mode of failure and the decrease in compressive strength leads to a decrease in the ultimate load by (10.13%) compared to (0%) RA replacement ratios.

- (75%) replacement ratio

Same as for (50%) replacement ratio, the mode of failure of the beams changed from flexural failure to shear failure due to the reasons discussed above, but the (75%) beam went directly to shear failure, which can be observed from the decrease in the deflection compared to (0%) RA.

On the other hand, the ultimate load was reduced by (27.08%) compared to (0%) RA due to the change in the mode of failure and the decrease in compressive strength.

3.4 Effect of recycled aggregate and elevated temperature on reused-steel reinforcement beams

- Fully natural aggregate beams

The elevated temperature led to a decrease in the ultimate strength by (5.92%) and also it caused an increase in the ultimate deflection by (8.53%).

It can be concluded that the elevated temperature causes a reduction in the beam's modulus of elasticity as well as a decrease in the concrete compressive strength, which leads to an increase in deflection and a decrease in the ultimate strength.

- (25%) replacement ratio

Comparing (25%) RA replacement ratio beams with (0%) RA beams subjected to elevated temperature shows that the ultimate strength decreased by (14.25%) due to the effect of the elevated temperature and the RA. Also, there was an increase in deflection by (17.08%) respectively, which shows a decrease in the beam's elastic modulus.

- (50%) replacement ratio

The mode of failure changed from flexural failure to shear failure, and the beams went directly to shear failure, which can be observed from the decrease in deflection.

On the other hand, the ultimate load was reduced by (34.76%) compared to (0%) replacement beams due to the change in the mode of failure and the decrease in the compressive strength.

- (75%) replacement ratio

Same as for (50%) replacement ratio, the mode of failure for the beams changed from flexural failure to shear failure, but for (75%) there was an increase in the deflection of the beams compared to (0%) replacement beams, so the beams were going towards flexural failure, but at the end, the mode of failure was a shear failure.

Also, the change in the mode of failure and the decrease in compressive strength lead to a decrease in ultimate load by (40.89%) compared to (0%) replacement beams.

3.5 Effect of reused-steel reinforcement on the behavior of recycled aggregate beams

- Fully natural aggregate beams not subjected to elevated temperature.

Beams with reused-steel reinforcement had (12.59%) lower ultimate load than those made with new steel reinforcement, and this is because the reused-steel reinforcement had lower-yielding strength than new steel reinforcement.

The type of failure for both types of steel reinforcement was the same, but the reused-steel had (47.28%) higher deflection than new steel and lower elastic modulus.

- Fully natural aggregate beams subjected to elevated temperature.

Beams with reused-steel reinforcement had (13.81%) lower ultimate load than those made with new steel reinforcement, and this is because the reused-steel reinforcement had lower-yielding strength than new steel reinforcement. Also, the percent decrease in the ultimate load is very close to the percent decrease occurred for beams that were not subjected to elevated temperature, which shows that the effect of the temperature was the same on both types of steel reinforcement beams.

The type of failure for both types of steel reinforcement was the same, but the reused-steel had (29.96%) higher deflection than new steel and lower elastic modulus.

- (25%) replacement ratio

Beams with reused-steel reinforcement had (23.21%) lower ultimate load than those made with new steel reinforcement, and this can be explained that the reused-steel reinforcement has lower-yielding strength than new steel reinforcement.

The type of failure for both types of steel reinforcement was the same, but the reused-steel had (4.39%) higher deflection than new steel and lower elastic

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modulus, and the percent increase in deflection for (25%) beams subjected to elevated temperature was higher than the percent increase in deflection for (0%) beams subjected to elevated temperature.

- (50%) replacement ratio

Beams with both types of steel reinforcement had the same type of failure, which makes it clear that the shear failure occurred due to the decrease in concrete shear strength due to the RA and the elevated temperature.

Beams with reused-steel reinforcement had (37.44%) lower ultimate load compared to those made with new steel reinforcement, this decrease in the load happen due to two facts:-

a) The effect of the dowel action
b) The deformations on reused-steel reinforcement were very small, and in some bars there were no deformation which led to a decrease in the friction between the flexural steel reinforcement and the stirrups causing the stirrups to slide on the flexural bars leading to an increase in crack width at lower load.

Reused-steel beams had (56.91%) lower deflection than new steel as the reused-steel reinforcement had a sudden shear failure while the new steel reinforcement had a flexural-shear failure.

- (75%) replacement ratio

Beams with both types of steel reinforcement had the same type of failure, which makes it clear that the shear failure occurred due to the decrease in concrete shear strength due to the RA and the elevated temperature.

Beams with reused-steel reinforcement had a lower ultimate load by (30.12%) than those made with new steel reinforcement, this decrease in the load can happen due to two facts:-

a) The effect of the dowel action
b) The deformations on reused-steel reinforcement were very small, and in some bars, there was no deformation which led to a decrease in the friction between the flexural steel reinforcement and the stirrups causing the stirrups to slide on the flexural bars leading to an increase in crack width at lower load.

Reused-steel beams had (107.61%) higher deflection than new steel as the new steel reinforcement had a sudden shear failure while the reused-steel reinforcement had a flexural-shear failure.

3.6 Comparison between results obtained in this experiment and results obtained by (Bsisu and Hammad 2021, Unpublished Master's degree thesis)

(Bsisu and Hammad 2021), studied the effect of the RA concrete and reused-steel reinforcement on the behavior of concrete beams without subjecting the beams to elevated temperatures.

- 0% recycled aggregate

The percent of reduction in the ultimate load was very close for both temperatures, while the increase in the ultimate deflection for beams subjected to elevated temperature was more than double what occurred for beams at (25) °C.

- 25%,50%,75% recycled aggregate

The percent reduction in the ultimate load for beams subjected to elevated temperature was much higher than that happened for beams at (25) °C. However, for (25% and 75%) RA replacement, there was a big difference in the percent of increase of the ultimate deflection for beams subjected to elevated temperature compared with beams at (25) °C, while for (50%) replacement, there was a decrease in the ultimate deflection for beams subjected to elevated temperature while there was an increase in the ultimate deflection for beams at (25) °C.

CONCLUSIONS

Based on the experiment and the data analysis, the following can be concluded:

- The (25%) recycled aggregate mix had the closest properties to fully natural aggregate mix before and after subjecting it to elevated temperature

- Beams made of new steel reinforcement and fully natural aggregate concrete had the largest carrying capacity after being subjected to elevated temperature.

- Beams made of reused-steel reinforcement and fully natural aggregate concrete and (25%) recycled aggregate had (13.81% and 23.21%)) less compressive strength than beams with new steel reinforcement, respectively.

- Comparing the reduction of strength for beams made of reused-steel and new steel before and after being subjected to elevated temperature, the reduction accrued in beams with fully natural aggregate was very close in both cases while a huge drop occurred in (25%) recycled aggregate beams.

- Using reused-steel reinforcement may be more economical, while it's safer to be used with fully natural aggregate for structures that have a risk of fire, or with (25%) recycled aggregate for the structure where the chance of being burned is close to zero.

- The change in the mode of failure from flexural to shear was due to the fact that the beam had a flexural capacity almost equal to the shear capacity and that the increase in the recycled aggregate causes a decrease in the shear capacity of concrete.

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