https://doi.org/10.26682/sjuod.2023.26.2.5

Journal of University of Duhok., Vol. 26, No.2 (Pure and Engineering Sciences), Pp 39-47, 2023
(Special Issue)

STUDYING STEEL-RECYCLED AGGREGATE CONCRETE BOND–SLIP BEHAVIOR USING DIGITAL IMAGE CORRELATION

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(Accepted for Publication: November 27, 2023)

ABSTRACT

The present study has two points of interest, the first point is steel-recycled aggregate concrete bond behavior, and the second point is the reliability of digital image correlation in tracking experimental deformations. Recycled aggregate concrete exhibits lower mechanical properties than natural aggregate concrete, as international standards were designed for natural aggregate concrete, so their applicability to recycled aggregate concrete is still ambiguous. In this study, five mixes were designed to verify the steel-recycle aggregate concrete internal bond-slip behavior, for five different replacement ratios (0%, 25%, 50%, 75%, and 100%), the test was supported by the DIC technique for getting the slip, adding to LVDT for verifying the results. The GOM program can analyze the test video, but this takes a lot of time. For getting the steel slip using the GOM program, a series of frames were extracted from the test video via the VLC media player program, and converted to black and white colors using the XnViewMP program to be analyzed in the 2D GOM program.

The steel-recycled aggregate concrete bond-slip curves obtained from the Digital Image Correlation (DIC) technique using the 2D GOM program were comparable with those obtained from LVDT, which means that the DIC technique is a reliable method for tracking experimental deformations.

The experimental results showed that the compressive strength decreased when the replacement ratio increased, where the decrease was 7.6%, 6.6%, 9.3%, and 13% for replacement ratios of 25%, 50%, 75%, and 100%. Bond strength decreased when the replacement ratio increased, where the decrease was 23.7%, 25.7%, 30.5%, 34.9% for replacement ratios 25%, 50%, 75%, 100%. There was no clear relationship between the slip and replacement ratio. A comparison with the international standards for bond-slip curves showed that the model of Harajli gives close results for steel–recycled aggregate concrete.

KEYWORDS**:** DIC; pullout test; bond-slip; concrete.

1. INTRODUCTION

Most constructions have reached their lifespan end, and replacing them requires new building materials and causes lots of debris and waste building materials that end up in landfills. Recycling this debris provides building materials and solves landfill environmental problems. However, recycled aggregates have less quality than natural ones, though they still fulfill the standard requirements [Fang et al. 2007]. Recycled Aggregate Concrete

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(RAC) mechanical properties are still the focus of researchers' interest, where the effect of replacement ratio is a crucial factor. The Bond between steel and RAC is responsible for transferring the axial forces between both materials and plays a major role during earthquakes, where premature bond failure may lead to catastrophic results. To define the development length and prevent early bond failure of reinforced concrete members, a comprehensive understanding of the bond behavior is vital. Many researchers have studied the bond strength of recycled aggregate concrete (RAC) [Seara-Paz et al. 2013]. Some of these researchers found that bond strength decreased with the increment in replacement ratio, while others concluded that there is no clear relationship between bond strength and replacement ratio [Xia and Falkner 2007], [Wardeh et al. 2017]. Prince et al. concluded that for treated recycled aggregate, bond strength increases with the increment of the replacement ratio [Prince et al. 2013].

Experimental deformations and strains of concrete can be measured using gauges replaced on the prospective crack positions. It may need many gauges to cover all possible crack places, however, Digital Image Correlation (DIC) techniques can be used to register deformations and strains depending on tracking subsets through the experimental procedure. In this research, the DIC technique was used for obtaining slips in the pullout test and comparing the results with the results obtained from traditional techniques like LVDT. The 2D GOM 2019 program can analyze short test videos, but it takes too long time to finish the process, for this reason, photos will be extracted from the video using special programs, which will decrease the analyzing time.

2. EXPERIMENTAL PROCEDURE

In this study five mixes were designed according to ACI 211, for verifying the steel–recycled aggregate concrete bond behavior, with different replacement ratios (0%, 25%, 50%, 75%, 100%), while the plasticizer was fixed to 1% of cement weight. Three cubic specimens for each mix were cast with dimensions of $150 \times 150 \times 150$ [cm^3], and 14 [mm] ribbed rebar in the middle of the specimens, with bond length, equal to five times steel diameter. For defining the compressive strength of the mixes, three cylindrical specimens were cast for each mix.

A Portland cement type I-32.5 with a specific gravity of 3.1 was used. A super plasticizer "Daracem SP6" was used, which fulfills ASTM-C-494-Type F.

The recycled coarse aggregates were obtained by crushing and sieving waste concrete from debris in the laboratory, where crushing and sieving were performed manually. The natural coarse aggregates (NCA) were crushed stone, and natural ordinary sand was used for all mixes.

The material proportions for the reference NAC mix for 1 m^3 in Kg are presented in **Table (1**, and the physical properties of the aggregates are shown in **Table (2**.

Table (1):- Concrete mix proportions

Constituents	Gravel 6/20	Sand 0/6	Water	Cement	Plasticizer
Dosage Kg/m3	1127	672	200	400	1

The yield strength of the steel is F_y=420 [MPa]. The geometric characteristics of the ribs are presented in **Error! Reference source not found.**.

Table (2):- The physical properties of the aggregates

	Natural aggregates	Recycled aggregates
Relative density (oven dry)	2.56	2.34
Bulk density (oven dry)	2.3	2.26
Moisture content 24h	3.3%	7.7%

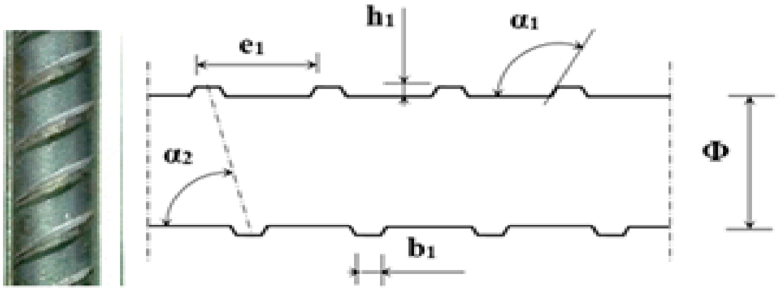

Fig.(1):- The ribbed steel rebar used in the test

Table (3):-The geometrical characteristics of the ribs

Φ(mm)	h_1(mm)	b_1(mm)	e_1(mm)	A_s(mm^2)
14	1.1	1.4	9	153
16	1.2	1.6	9.6	201

3. DIGITAL IMAGE CORRELATION DIC

Displacements; like slips in the pullout test; can be calculated through the 2D DIC technique, by analyzing a video that was taken through the test, which takes a long time to be analyzed, or a series of frame photos distracted from the video, which takes smaller time than that required for analyzing a video. A calibration process was implemented for the 2D DIC technique using different manual speckling patterns (video and still images were calibrated), where the best pattern was adopted for the specimens. A white and black speckling pattern was applied on the targeted plane on the specimen, while one camera (a Sony IMX576 wide camera) with a flash was fixed in front of the plane and normal to it. The video contains 30 frames per second and a frame every second was extracted. Pullout test was conducted using a TECNOTEST 5000 KN machine, with manually controlled speed. For verifying the results calculated from the DIC technique, a comparison with traditional techniques like LVDT will be conducted. Figure 2 shows the specimen in the machine with the sparkled pattern.

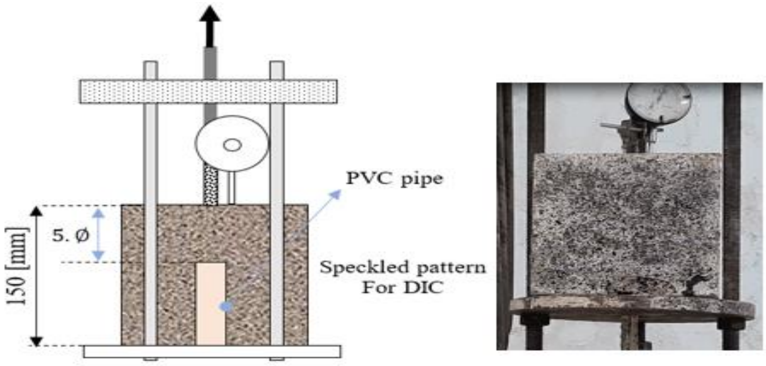

Fig.(2):- Pullout test supported with DIC technique

https://doi.org/10.26682/sjuod.2023.26.2.5
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In the present study, the GOM program was used to analyze the photos that were extracted from the video using the VLC media player program, and converted to gray color using the XnViewMP program. The GOM program analyses the displacements by tracking a targeted subset, and comparing it to a reference subset, as shown in **Error! Reference source not found.**.

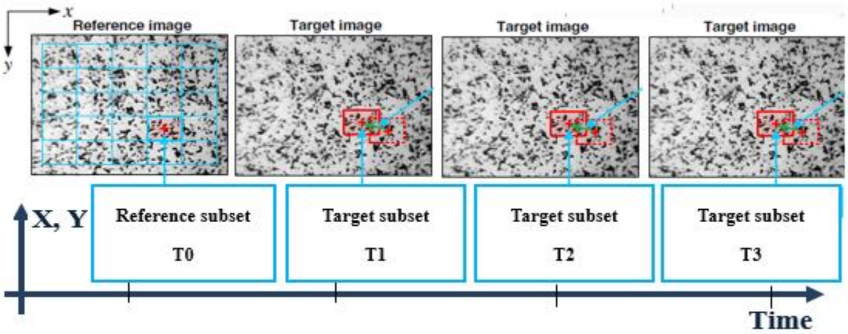

Fig.(3):- The Reference and targeted subsets through time

The slip registered in the pullout test can be calculated through many methods in the GOM program, one of them is the displacement in the Y direction, as the steel is fixed and concrete cubic is the movable part.

There is another way which is the Extensometer that gives the distance between two points, but the steel rebar and the cubic are in different planes so this method is hard to apply here. After getting the slip with time from DIC, results were exported to EXCEL for extracting bond stress–slip curves.

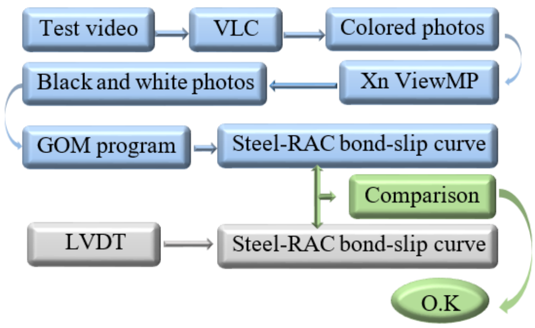

Fig.(4):- Flowchart of the DIC methodology

Results obtained from the DIC technique, which is slip-time, see **Error! Reference source not found.**, were compared with those obtained from LVDT, and the comparison is presented in **Fig.(1**.

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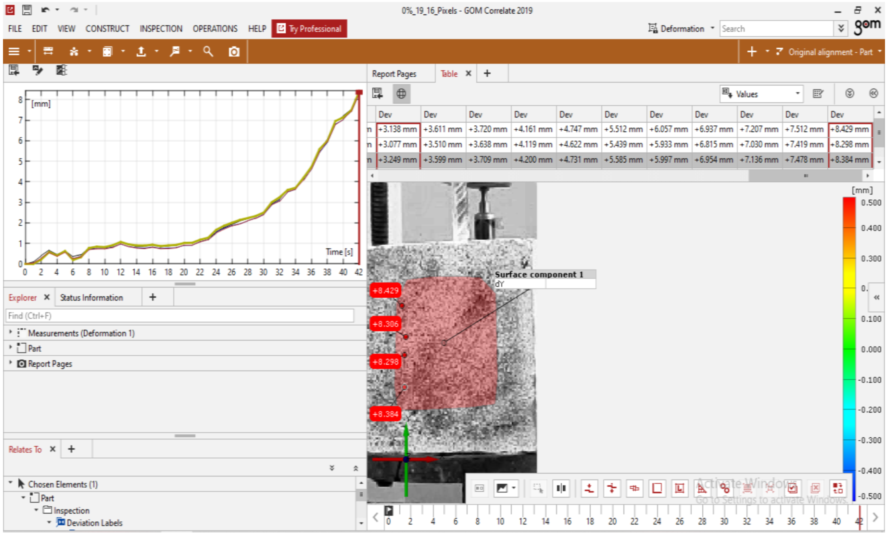

Fig.(5):- Slip – Time curve obtained from the DIC technique

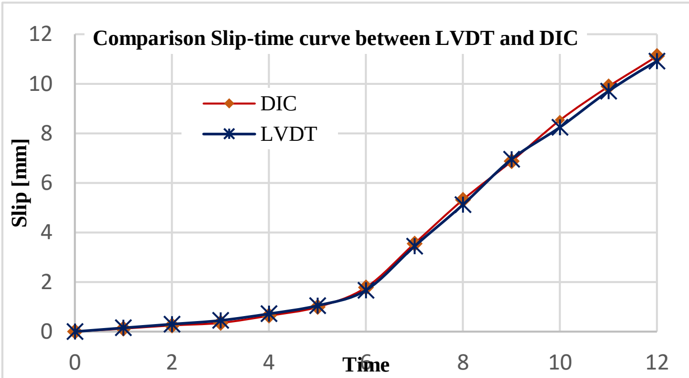

Fig.(1):- Comparison between slip–time curves obtained from DIC and LVDT.

4. RESULTS AND DISCUSSION

The comparison between slip-time curves obtained from DIC and LVDT exhibited a good agreement, see **Fig.(1**, which means that DIC technique is reliable for tracking deformations. This results are similar to the findings of Bello et al. [Bello et al. 2023].

The compressive strength was investigated according to NF EN 196-1, the results are shown in table 4.

The pullout test was performed on the 15 concrete specimens. The tension machine INSTRON (500 [KN]) was used to obtain the load values, where the loading speed was manually controlled. All specimens' failure modes were pull-out mode.

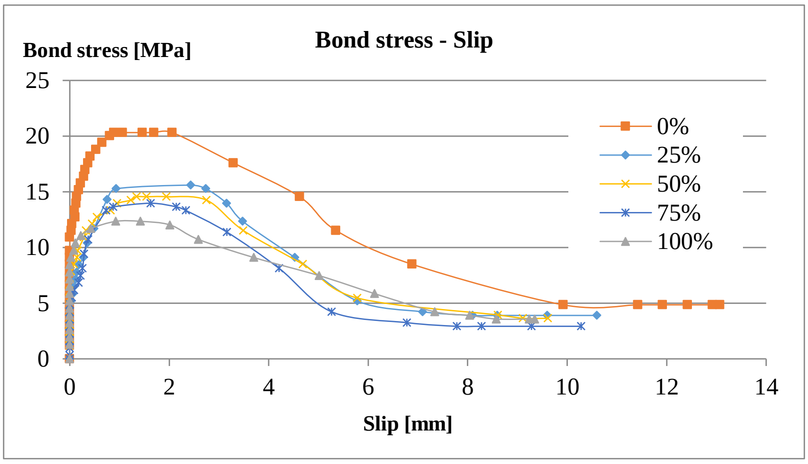

Fig.(2):- The bond stress – slip from LVDT

It can be noticed from **Fig.(2** that the bond-slip behavior for all mixes includes four stages, the first one is the linear stage, and the slip is very small. In the second stage, nonlinear behavior is noticed while the slip is still small. The slip became larger in the third stage, then the maximum stress was reached, after that, stresses started to decrease towards the residual strength and the slip continued to increase for the same stress till complete failure.

The mean values of the compressive strength of concrete and bond strength for all mixes are presented in

Table (4. It can be noticed that the compression strength decreased with the increase in replacement ratio, where the decrease was 7.6%, 6.6%, 9.3%, and 13% for replacement ratios of 25%, 50%, 75%, and 100%. The bond stress decreased also with the increase of the replacement ratio, and this increase was 23.7%, 25.6%, 30.45%, and 34.9% for replacement ratios of 25%, 50%, 75%, and 100%. There was no clear relationship between the slip and residual stress with the increase in replacement ratio. Similar observations were obtained by Xiao [Xiao 2018].

Table (4):-The mean values of the compressive strength of concrete and bond strength for all mixes

Ratio	F'_c [MPa]	τ_u [MPa]	S1 [mm]	S2 [mm]	S3 [mm]	τ_f [MPa]
0%	25.90	19.31	1.19	2.38	9.48	4.55
25%	23.92	14.73	1.19	2.72	8.29	3.79
50%	24.20	14.36	1.28	3.04	8.45	3.84
75%	23.50	13.43	1.17	2.49	7.85	2.71
100%	22.51	12.56	1.08	2.29	8.43	3.36

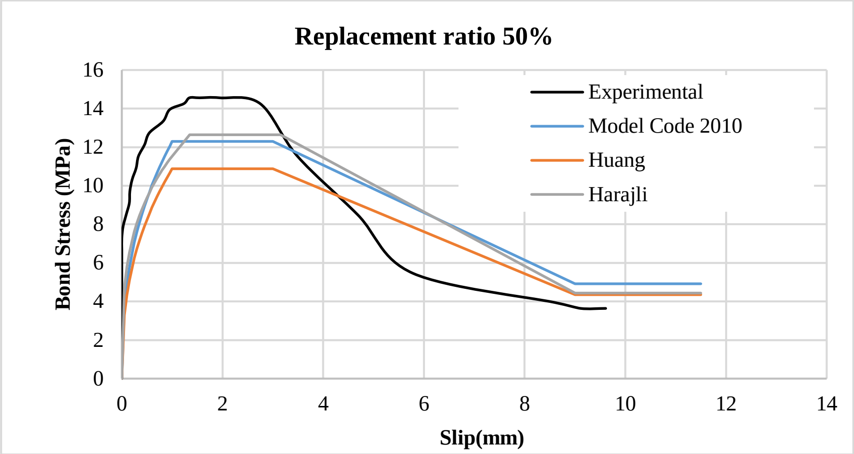

Fig.(3):- Comparison between experimental bond-slip curve for 25% mix and standard bond-slip curves from references

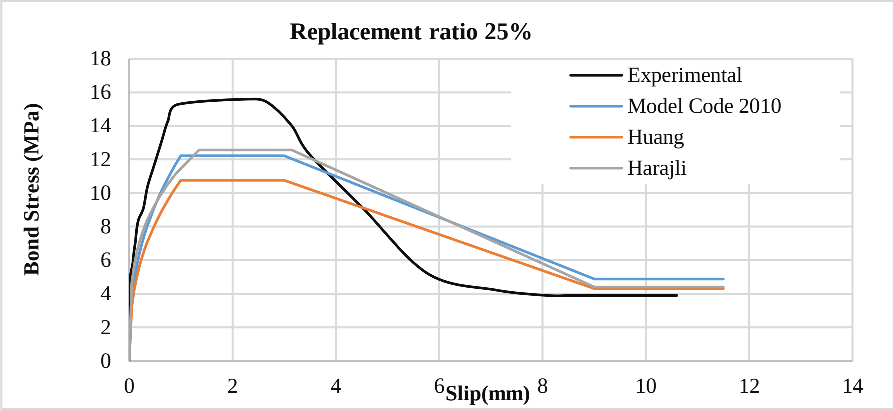

Fig.(4):- Comparison between experimental bond-slip curve for 50% mix and standard bond-slip curves from references

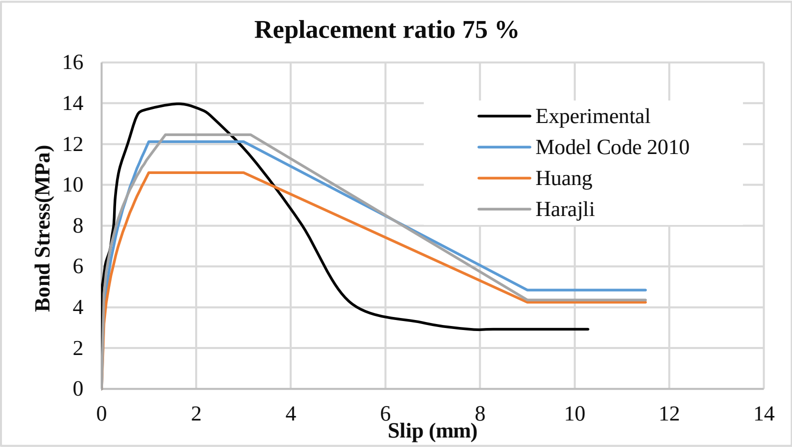

Fig.(5):- Comparison between experimental bond-slip curve for 75% mix and standard bond-slip curves from references

Figures 7, 8, 9, and 10 represent the comparison between experimental bond stress-slip curves with those obtained from the empirical curves of Harajli, Haung, and the CEB model code. It can be noticed the CEB model and Harajli model are applicable to recycled aggregate concrete.

5. CONCLUSION

The results of the present study concluded the following:

- The compression strength decreased with the increase in replacement ratio, where the decrease was 7.6%, 6.6%, 9.3%, and 13% for replacement ratios of 25%, 50%, 75%, and 100%.
- For the same plasticizer ratio and water-to-cement ratio, ribbed steel-recycled aggregate concrete bond behavior decreased with the increase of replacement ratio, where the decrease was **23.7%, 25.7%, 30.5%, 34.9%** for replacement ratios 25%, 50%, 75%, 100%.
- CEB and Harajli bond-slip models are applicable for recycled aggregate concrete.
- The results of the slip calculated from the DIC technique and LVDT are comparable.

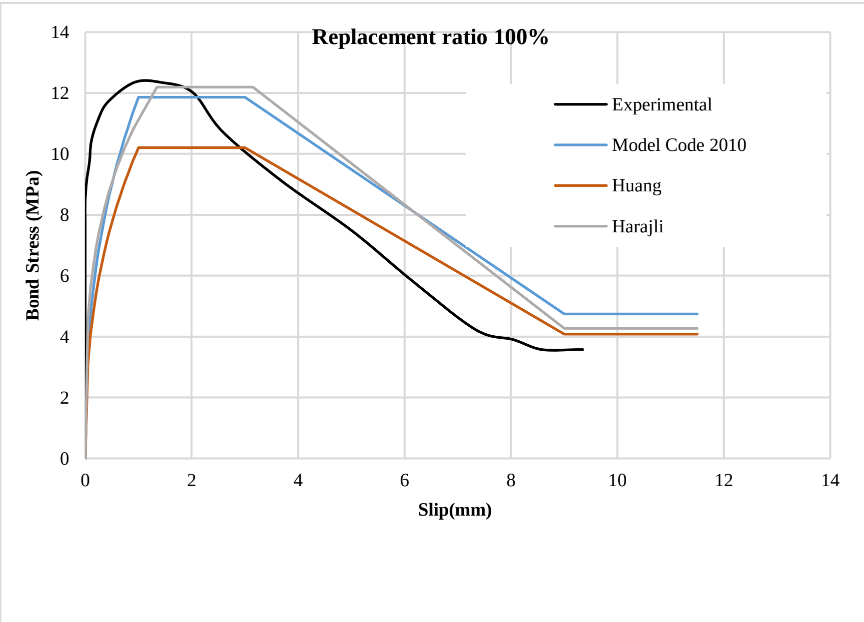

Fig.(6):- Comparison between experimental bond-slip curve for 100% mix and standard bond-slip curves from references.

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