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Shear Transfer Behavior of Non-Coarse Aggregate Polymer Concrete

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Abstract : *This study is aimed to investigate effect of absence coarse aggregate on the shear transfer behavior along the interface between the two parts of push-off test specimens casted using non-coarse aggregate polymer concrete experimentally and numerically. The specimen consists of two parts, first part was casted and the interface surface was prepared after 28 days from casting, then second part was casted. The parameters considered in this study were interface roughness, use of epoxy paint applied on the interface just before casting the new concrete and the use of steel dowels. A three-dimensional finite element method (FEM) model of push-off test was also carried out. The model considered the effect of interface status and using dowels steel reinforcement embedded in both parts of old and new specimens. Both the experimental and FEM results can predict the ultimate shear strength of the interface. The results obtained from both experimental and FEM showed that the ultimate shear strength of polymer concrete is approximately 55% from the corresponding ultimate shear strength of normal concrete. Also, both ACI and EC codes were underestimating the ultimate shear strength for polymer concrete, using dowels with rough interface is highly recommended. Finally, binding material is not recommended for interface treatment for polymer concrete.*

Keywords : *Shear Transfer, Polymer Concrete, non-coarse aggregate, Push-off specimens.*

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I. Introduction

Polymer concrete was used for some structural elements and roads because of its high workability, light weight, good strength, self-compacted, low permeability, and fast curing time. The polymer concrete usually consists of two components, the first component is powder which can be made from recycling building materials. While the second component was a liquid polymer resin. The both mechanical and chemical properties of many types of polymer concrete were studied, the main important property of polymer concrete is the shear strength because Shear transfer behavior significantly contribute to the shear resistance design in concrete structure, such as shear walls, deep beams, specially repaired or strengthened structure elements. Several researches carried out to investigate the behavior of shear transfer between concrete interfaces. [1-10]

This study presents the effect of absence coarse aggregate on the interface shear transfer behavior of the push-off test specimens casted with non-coarse aggregate polymer concrete. An experimental and numerical study were carried out for this investigation.

In this study an experimental and numerical program was carried out. The experimental program using push-off specimens consisting of two parts cast at different times to evaluate the shear transfer along the interface between surfaces. The variables studied include roughening of interface surface, painting the old surface with binding materials and using steel dowels embedded in old concrete. All surface treatments of the connections were made after the complete hardening of the old polymer concrete part to achieve the main purpose of this study. Test results are presented and discussed herein after. While the numerical analysis was carried out using ABAQUS [11] finite element software program. Also, the results obtained from FEM were compared to both ACI code [12] and EC code [13] equations for estimating the ultimate shear at the surface-to-surface connection.

II. Experimental Program

2.1. Details of test specimens

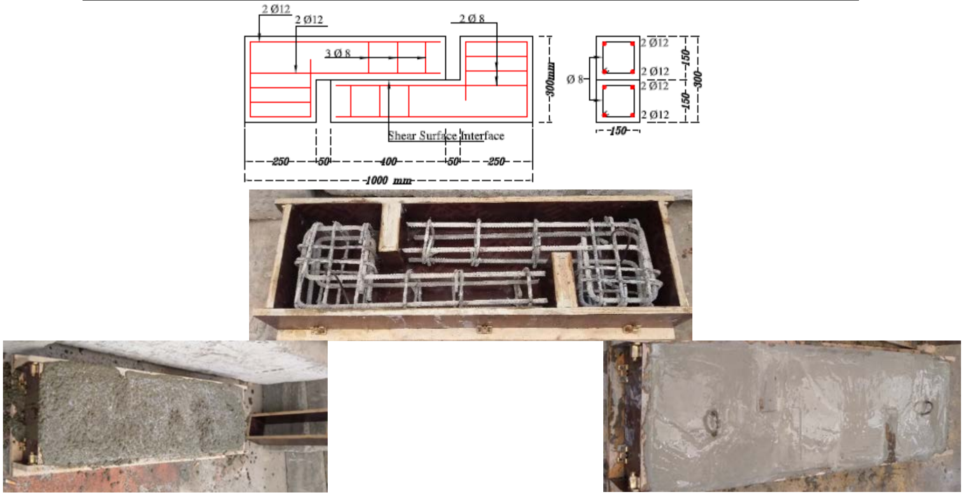
Six push-off specimens were prepared and casted, one was casted monolithic using normal concrete and the other five specimens were casted using polymer concrete without coarse aggregate, the details of all specimens are listed in table (1). Each specimen was divided into two parts; the first part was casted first, in addition, after twenty-eight days the surface of interface of the first part was prepared according to the required parameter of the interface study. While the second part was casted on the prepared interface surface with the same type of polymer concrete mix.

The first and second specimens (SF1 & SF2) were casted monolithically using normal concrete and non-coarse aggregate polymer concrete respectively. The interface of the third specimen (SF3) was left as smooth interface surface between old and new polymer concrete. While the interface of the fourth specimen (SF4) was prepared as rough interface surface between old and new polymer concrete. In addition, an epoxy binding material was applied to the interface of first part of specimen (SF5) immediately before casting the second part of the specimen with polymer concrete. Finally, two 10 mm dowels were bonded to the first part of the last specimen (SF6) using epoxy resin, the embedded length was 10 times the dowel diameter, with the drilled hole diameter equal to the dowel diameter plus two millimeters. After that, the second part was casted, as shown in figure (1).

All specimens were reinforced with 12 mm high tensile steel (f_y = 460 MPa.), while the stirrups were 8 mm mild steel with f_y = 240 MPa. Both normal concrete and polymer concrete have a compressive strength of 25 MPa. Figure (2) shows Stress-strain curve of Polymer Concrete.

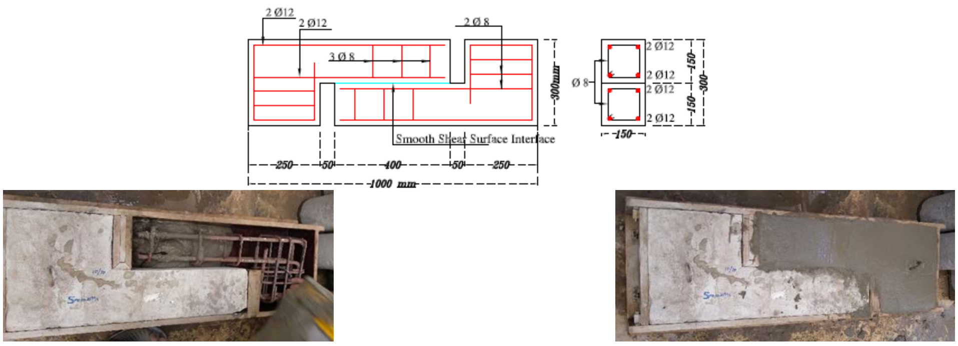
Table (1): Details of Test Specimens

Spec. No.	Conc. type	Interface condition	F_{cu} MPa	Dowels
SF1	normal	Monolithic	25	-
SF2	Polymer	Monolithic	25	-
SF3	Polymer	Smooth	25	-
SF4	Polymer	rough	25	-
SF5	Polymer	Smooth + binding material	25	-
SF6	Polymer	Smooth + dowels	25	2ϕ10

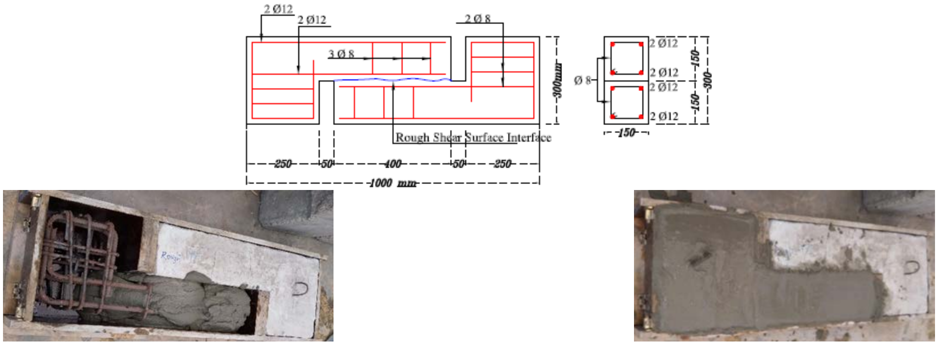


Normal concrete Polymer concrete

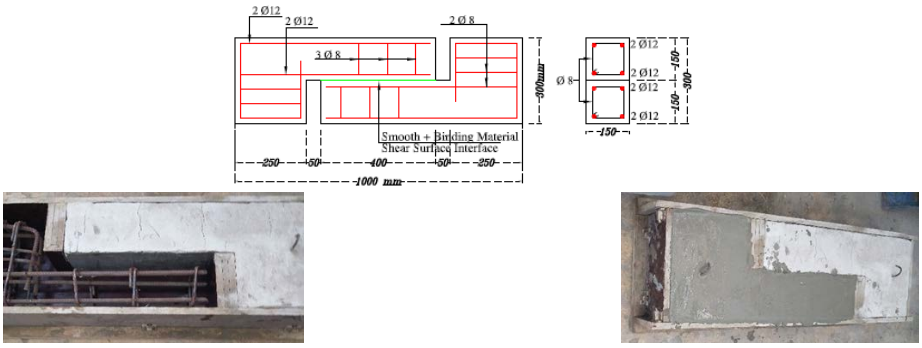
Details of monolithic Specimens SF1 and SF3



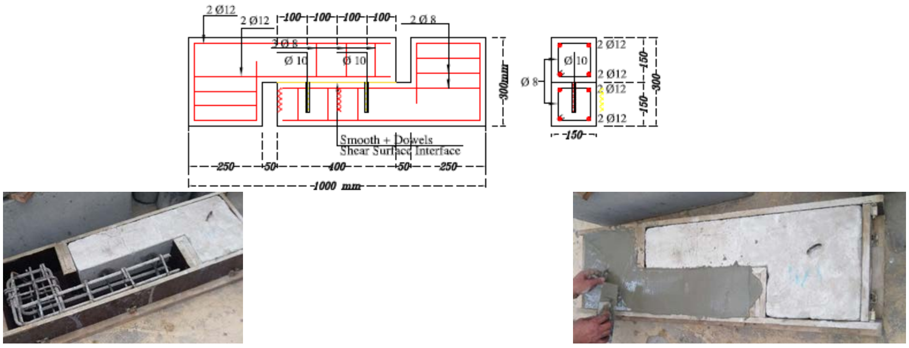
Details of Specimen SF3



Details of Specimen SF4



Details of Specimen SF5



Details of Specimen SF6

Figure (1): Details of Push-off sepecimens

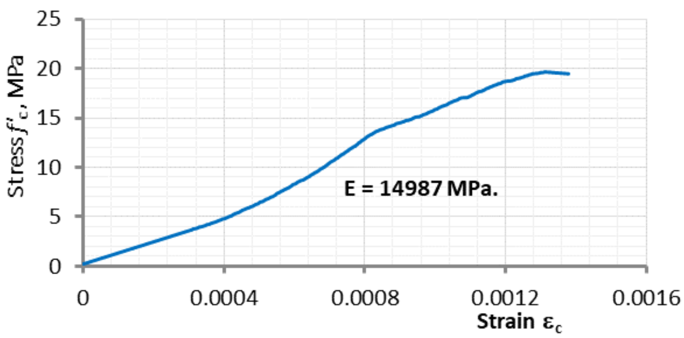


Figure (2): Stress-strain Curve for Polymer Concrete with non-coarse Aggregate

2.2. Test Setup and measurements

All specimens were tested horizontally as shown in Figure (3). The load was applied horizontally at the center of a rigid steel plate at one end of the specimen with a small rate. While the other end was supported to a rigid steel beam. All tested specimens were loaded gradually up to failure. The vertical and horizontal slip was measured at two points by using +50 mm linear variable differential transducer (PI-Gauge) at specified load level which recorded using load cell. The specimens were applied to a displacement central test performed by using data acquisition online computer system programmed using Lab View software, as shown in Figure (3).

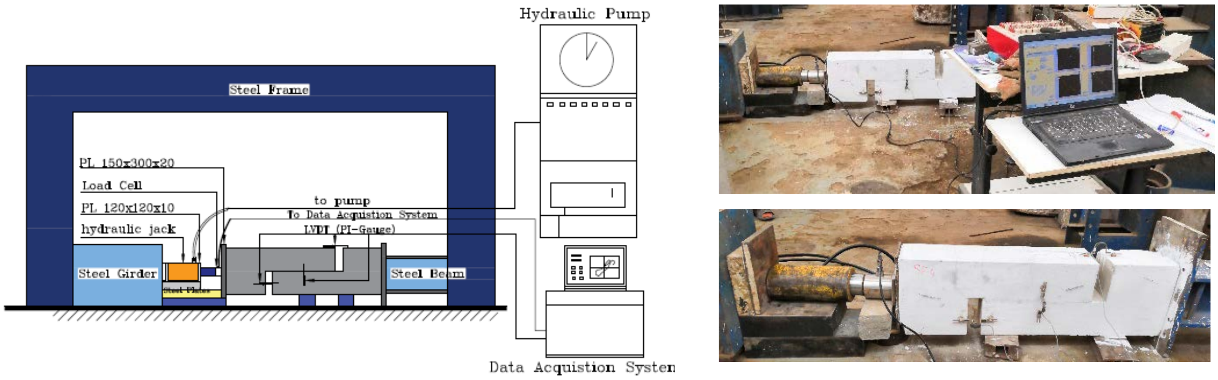


Figure (3) : Test Setup

III. Test Results

The results of mode of failure, applied loads versus specimens' slip (measured horizontally along the interface between the two parts of the specimen), and the effect of different studied parameters on the behavior of shear transfer along the interface between old and new polymer concrete will be presented for each specimen of the experimental program.

3.1. Mode of failure and cracking patterns

From the results it can be observed that the mode of failure for all specimens was due to shear-slip at the interface between old and new parts of each specimen. The cracking patterns are shown in figure (4).

The normal concrete monolithic specimen failed at the weak points of the interface, while the specimens with either smooth or rough interface surface failed at the straight interface line tacking very small layer from the casting new part of polymer concrete. On the other hand, the binding material made an insulation layer at the interface and weak the interface shear strength between old and new parts of polymer concrete. Finally, the dowels lead to make the interface between old and new parts very ductile.

SF1

SF2

SF3

SF4


SF5

SF6

Figure (4): Cracking Patterns and Failure mode of all tested Specimens

3.2. Shear– Slip characteristics

The ultimate capacity of tested specimens measured using load cell used for the data acquisition system for each specimen as mentioned in Table (2). The ultimate shear strength for normal concrete specimen SF1 is greater than the ultimate shear strength for all polymer concrete specimens as shown in figure (5). Comparing the ultimate shear strength at interface of all specimens and corresponding ultimate shear strength of the monolithic polymer concrete specimen SF2, it can be observed that;

The ultimate shear strength of the monolithic normal concrete specimen SF1 was 1.77 times the corresponding ultimate shear strength of the monolithic polymer concrete specimen SF2 due to the effect of absence coarse aggregate in polymer concrete. In addition; the absence of coarse aggregate caused no aggregate interlock at the cracked surface which decreased the shear strength at the interface of polymer concrete specimen. In this case; a reduction factor (k=0.55) was recommended to be used for estimating shear stress at the interface for polymer concrete.

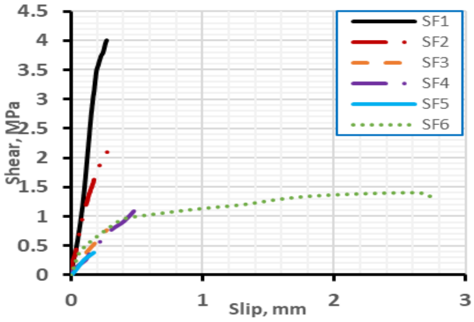
The ultimate shear strength for the specimens SF3 with smooth and SF4 with rough interface surface was found to be 0.34 and 0.51 times the monolithic shear strength specimen SF2. It can be noticed that increasing the roughness led to increase the ultimate shear strength of the interface between old and new polymer concrete.

While when paint binding material at the interface of specimen SF5, the ultimate shear strength was 0.17 times the monolithic specimen SF1, it can be noticed the interface treatment had insignificant effect on the value of ultimate shear strength of polymer concrete because it was making an insulation layer at the interface between the two specimens' parts as shown from in figure (4) of SF5 failure mode.

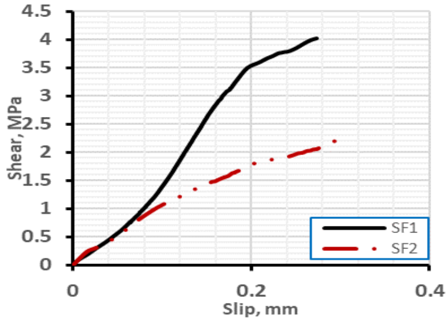
Finally, for the specimen SF6 with two dowels of 10 mm diameter and embedded length of 10 times its diameter in both parts of the specimens, the ultimate shear strength was 0.62 times the corresponding ultimate shear strength of the monolithic specimen SF2. While the slip for SF6 was 8.77 times the slip of SF2 due to the effect of dowels ductility on the interface slipping. From the experimental results, it can be found that using dowels are recommended for interface connecting between old and new parts of structure elements cast with polymer concrete, while using binding materials for painting the interface were not allowed with polymer concrete

Table (2): experimental results of tested specimens

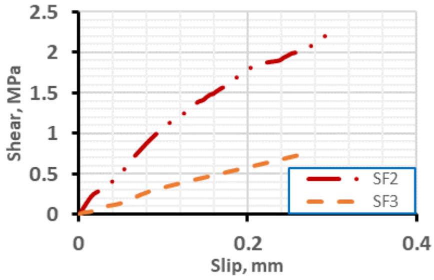
Spec. No.	Experimental results			τ_u / $\tau_{u, SF2}$	Δ_u / $\Delta_{u, SF2}$
	P_u, kN	Slip at ultimate load Δ_u, mm	Interface ultimate shear strength τ_u, MPa		
SF1	240.7	0.27	4.01	1.77	0.9
SF2	136.2	0.3	2.27	1	1
SF3	46	0.28	0.77	0.34	0.93
SF4	69.9	0.61	1.17	0.51	2.03
SF5	22.5	0.18	0.38	0.17	0.6
SF6	84.6	2.63	1.41	0.62	8.77



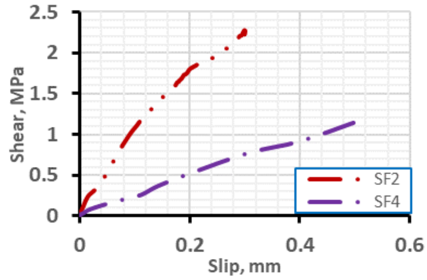
Shear-Slip for all Specimens



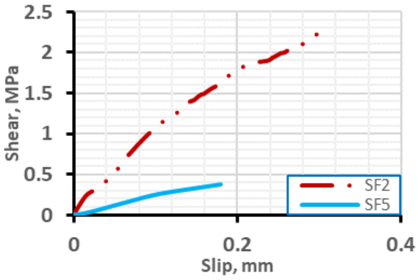
Effect of concrete type (SF1 vs SF2)



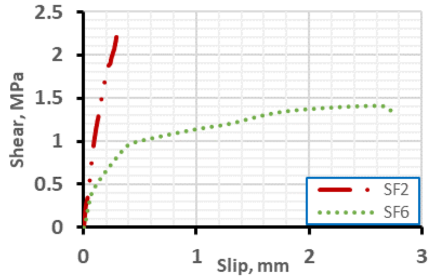
Effect of smooth interface (SF3 vs SF2)



Effect of rough interface (SF4 vs SF2)



Effect of binding material (SF5 vs SF2)



Effect of dowels (SF6 vs SF2)

Figure (5): Shear-Slip characteristics

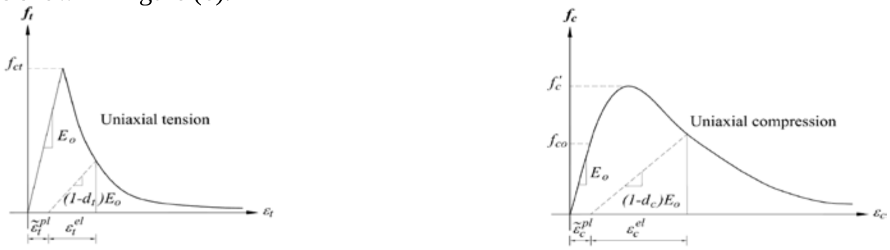
IV. Numerical Analysis

The finite element program ABAQUS [11] was used to study the behavior of reinforced concrete deep beams. The provided model was used to validate the results of experimental analysis of tested specimens with and without web openings.

V. Material Modeling of Tested Specimens

5.1. Concrete

The concrete damage plasticity in ABAQUS software [11] can be used for defining the material properties of concrete material of push-off test. The concrete damaged plasticity model assumes that the two main failure mechanisms in concrete are the tensile cracking and the compressive crushing. The evolution of the yield (or failure) surface is determined by two hardening variables, tension and compression equivalent plastic strains, respectively. Each of them is linked to degradation mechanisms under tensile or compressive stress conditions, as shown in figure (6).



(a) **(b)**

Figure (6): Response of Concrete Due To (A) Uniaxial Tension, (B) Uniaxial Compression.

5.2. Steel

The constitutive behavior of steel can be predicted using an elastic perfectly plastic model, as described in (ABAQUS /CAE 2017). In this approach, the steel behavior is elastic up to the yield stress. At this point, the material yields under constant load, as shown in Figure (7). The steel reinforcement embedded to the concrete assuming that there is a perfect bond between the concrete and the steel reinforcement.

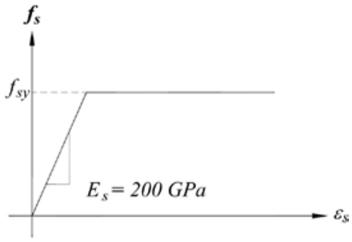


Figure (7): Stress-Strain Relationship for Steel Reinforcement.

5.3. Surface-to-Surface property modeling

The evaluation of shear strength across the shear plane was a directly influential factor for accurate simulation of shear transfer capacity. This interfacial zone between concrete layers was modeled with surface-to-surface contact. Damage of the traction–separation response for cohesive surfaces was used to simulate the degradation and eventual failure of the bond between two cohesive surfaces. The typical traction–separation response is depicted in Figure (8). The maximum stress criterion can be represented as:

$$\max\{\frac{\langle t_n \rangle}{t_n^o}, \frac{t_s}{t_s^o}, \frac{t_t}{t_t^o}\} = 1 \quad (1)$$

In this criterion, damage is assumed to initiate when the maximum contact stress ratio reaches a value of one. t_n, t_s and t_t represent the contact stress purely normal to the interface, along the first shear direction and along the second shear direction, respectively; and t_n^o, t_s^o and t_t^o represent the peak value of the contact stress.

The surface-to-surface shear stress is estimated as the friction action along the shear plane. The contact stress along the first shear direction t_s and along the second shear direction t_t are calculated by the equation $\tau = \mu\rho f_y$. Different friction factors μ are chosen to simulate different joint interface condition for different steel dowels to interface area ratio, ρ and f_y is the yielding stress for steel dowels.

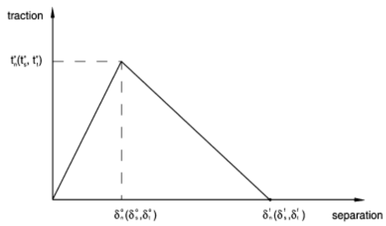
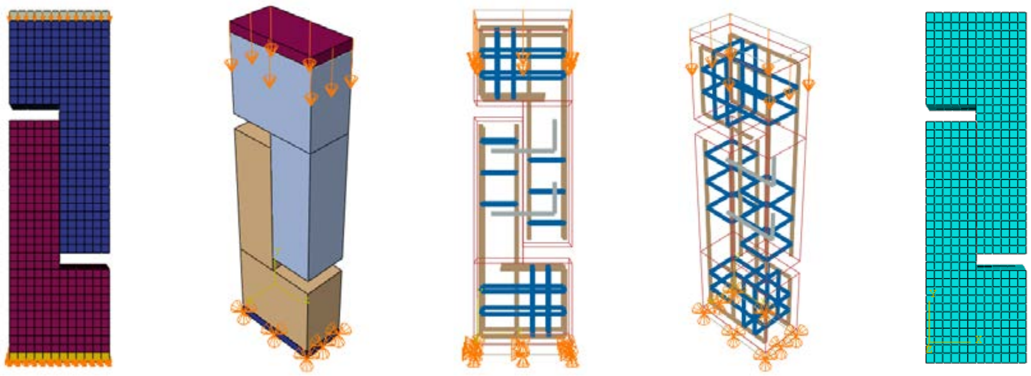


Figure (8): Typical traction-separation response with linear softening available in ABAQUS

VI. Model Validation

A three-dimensional finite element (FE) program 'ABAQUS' is used for the numerical analysis of all tested specimens. An 8-node solid element, C3D8R was used to model the both the concrete body and steel plates under applied load. While longitudinal reinforcement, stirrups, and dowels are model by using element T3D2. The monolithic specimens modeled as one unit, while the other specimens modeled as two L-shaped parts connected together with surface-to-surface contact taking into consideration the degree of interface roughness. The loading was applied at load-plates over the top of specimen, while the hinged supports were used. The details of FE model used in this validation is shown in Figure (8).



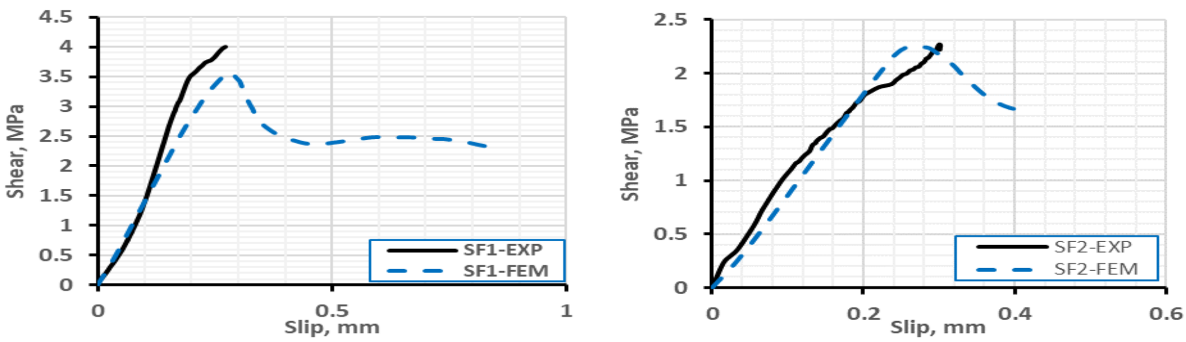
constraint, and loading   Reinforcement and dowels   Mesh

Figure (8) :3d-Model for push-off test used by ABAQUS

The ultimate shear strength obtained from FE model was compared with the results obtained from the experimental results. The modeled response verifies the ability of the selected model to capture the whole specimens' behavior up to failure and shows a good agreement to the experimental results. The results of the model can be used in validating and guiding experimental work. Table (4) show the FE model results compared to experimental results. It can be found that the FEM results for both ultimate shear stress and slip were matching the obtained results from experimental test, as shown in figures (9,10).

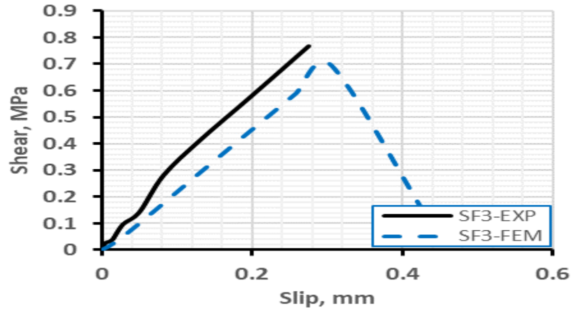
Table (4): Comparison of FEM results and experimental results all tested specimens

Spec. No.	Experimental results			FEM results			% τ_{FEM}/τ_{EXP}	% $\Delta_{FEM}/\Delta_{EXP}$
	P_u, kN	**Slip at ultimate load Δ_u, mm**	**Interface ultimate shear strength τ_u, MPa**	**P_u, kN**	**Slip at ultimate load Δ_u, mm**	**Interface ultimate shear strength τ_u, MPa**		
SF1	240.7	0.27	4.01	214.26	0.28	3.57	89	104
SF2	136.2	0.3	2.27	135.36	0.27	2.26	99.5	90
SF3	46	0.28	0.77	41.74	0.31	0.70	91	110
SF4	69.9	0.61	1.17	68.6	0.53	1.14	97.4	87
SF5	22.5	0.18	0.38	24.4	0.20	0.41	108	111
SF6	84.6	2.63	1.41	83.4	3.0	1.39	98.5	114

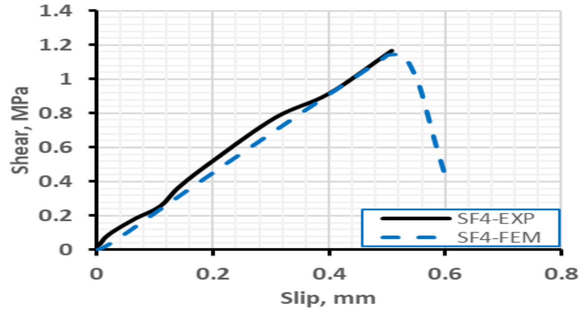


SF1   SF2

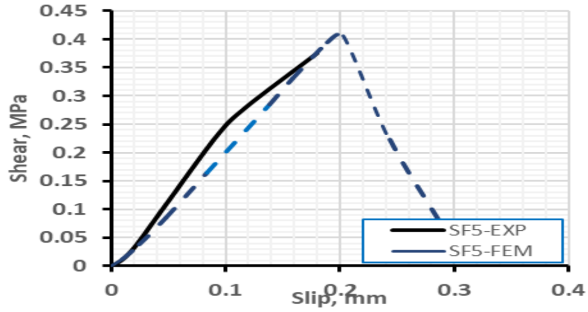
Fig. (9) FEM vs. Experimental results for monolithic specimens



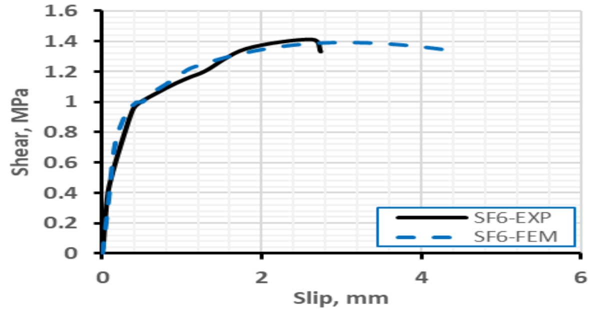
SF3 (smooth interface)



SF4 (rough interface)



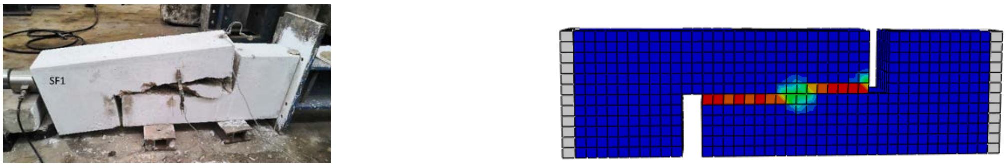
SF5 (binding material)



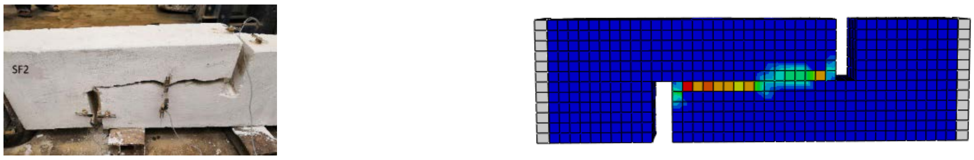
SF6 (smooth interface + dowels)

Fig. (10) FEM vs. Experimental results for Polymer Concrete specimens with different interface parameters

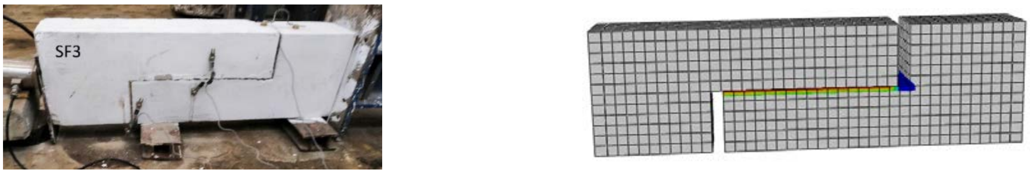
In additions, the results of interface failure for all tested specimens obtained from FEM matching were matching the corresponding results obtained from experimental test as shown in figure (11). For the specimens SF3, SF4, and SF5 the failure occurred along the interface and the cracking patterns nearly the same for both experimental and numerical results, while for the specimen with dowel SF6, the dowels were bend and the slip of this specimen is very larger than all other specimens due to the ductility of the embedded dowels.



SF1

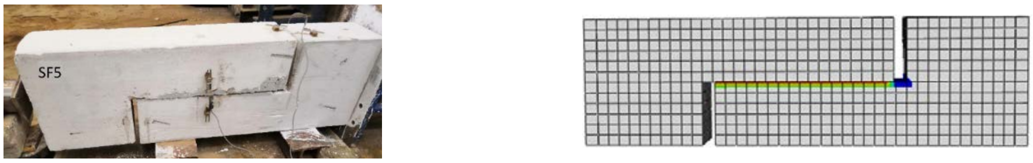


SF2

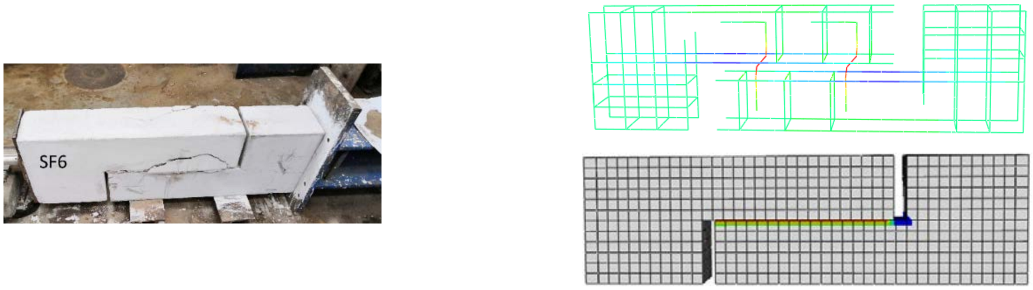


SF3

SF4



SF5

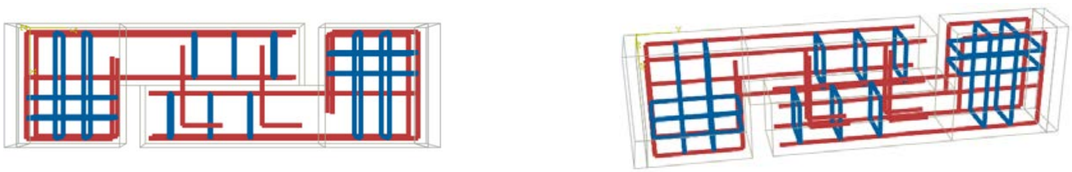


SF6

Figure (11): interface failure comparison between Experimental and FEM results.

The validating FEM was used for another parametric study to predict the shear transfer behavior of the polymer concrete, the parameters used with the verifying model were, the effect of roughening interface with dowels. Four specimens were simulated with FEM ABAQUS, first two FEM specimens were SF6, and SF7, with smooth, and rough interface respectively and every specimen had two dowels with 10 mm diameters connected the old and new parts of the specimens. While the other two FEM specimens were SF8, and SF9 all were with rough interface and 4 dowels with 10 mm, 12 mm and 16 mm diameter respectively connected the old and new parts of the specimens, as shown in figure (12). The results obtained from FEM showed that the ultimate shear strength at the interface was 139 MPa, 1.81 MPa, 2.13MPa., and 2.93 MPa. for SF6, SF7, SF8, and SF9 respectively, as shown in table (5).

From the FEM results it can be observed that the roughening and dowels had significant effect on the ultimate shear strength of the interface of polymer concrete specimens.



SF6 & SF7 SF8 & SF9

Figure (12): Details of Parametric study specimens

Table (5): FEM results of Parametric study specimens

Spec. No.	**Interface type**	$\tau_{u\ (FEM)}$
SF6	Smooth + 2 ϕ10 mm dowels	1.39
SF7	Rough + 2 ϕ10 mm dowels	1.81
SF8	Rough +4 ϕ10 mm dowels	2.13
SF9	Rough + 4 ϕ12 mm dowels	2.93

VII. Theoretical Analysis

The ultimate shear strength obtained from FEM push-off test for parametric study considering the effect of interface roughening and embedded dowels was compared to the results from both ACI [12] and EC [13] equations for predicting shear transfer as follow;

The ACI formula was as follow:

$$V = \mu . A_{vf} . f_y \tag{2}$$

where,

V = Ultimate shearing force.

A_{vf} = Area of shear friction reinforcement.

f_y = Yield strength of shear friction reinforcement.

μ = 1.40 λ, 1.00 λ and 0.60 λ for monolithic, rough and smooth surface.

λ = 1.0, 0.85 and 0.75 for normal weight, sand-light weight and light weight concrete.

According to EC code, the shear transfer force can be calculated in the absence of normal force on the shear plane as follows:

$$Q_u = [\mu \sin \alpha_f + \cos \alpha_f] . A_{vf} \frac{f_y}{\gamma_s} \quad (3)$$

where,
Q_u = Ultimate shearing force.
α_f = Intersecting angle between shear plane and shear friction reinforcement.
f_y = Yield strength of shear friction reinforcement.
A_{sf} = Shear friction reinforcement.
μ = 1.20, 0.80 and 0.50 for monolithic, rough and smooth surfaces, respectively.

Table (6) shows the comparison between the ultimate shear strength obtained from both the experimental and the parametric study of the FEM and those computed from the codes of practice. As can be seen, the interface ultimate shear strength obtained from ACI code were smaller than both experimental and FEM results by average (0.38% – 0.88%). Similarly, the interface ultimate shear strength obtained from EC code were smaller than both experimental and FEM results by average (0.37% – 0.82%). It can be showed that the increasing of dowels area lead to increase the interface ultimate shear strength and results obtained from both ACI and EC codes were convergence to the results obtained from FEM results. Then, it is recommended when increasing the embedded dowels area to apply a reduction factor to both ACI and EC formula when using them for estimating the interface ultimate shear strength of the polymer concrete specimens.

Table (6): Comparison between test results and codes of practice

Spec. No.	Interface type	τ_u (EXP)	$\tau_{u\,(FEM)}$	$\tau_{u\,(ACI)}$ (light weight concrete)	τ_u (ECCS)	$\tau_{u\,(ACI)}$ / $\tau_{u\,(EXP)}$	$\tau_{u\,(ACI)}$ / $\tau_{u\,(FEM)}$	$\tau_{u\,(ECCS)}$ / $\tau_{u\,(EXP)}$	$\tau_{u\,(ECCS)}$/ $\tau_{u\,(FEM)}$
SF6	Smooth + 2 ϕ10 mm dowels	1.41	139	0.54	0.52	0.383	0.388	0.369	0.374
SF7	Rough + 2 ϕ10 mm dowels	--	1.81	0.90	0.84	--	0.497	--	0.464
SF8	Rough +4 ϕ10 mm dowels	--	2.13	1.81	1.67	--	0.85	--	0.784
SF9	Rough + 4 ϕ12 mm dowels	--	2.93	2.6	2.41	--	0.887	--	0.823

From the both the experimental and FEM results, the coefficient of friction μ must be decreased by multiplying a reduction factor due to the effect of the absence of coarse aggregate in polymer concrete to be safer. Both ACI code and the EC code can be used for computed the ultimate shear strength of polymer concrete. It is recommended when using either ACI or EC codes formulae to reduce the coefficient of friction μ by a correlation factor when increasing both diameter and number of embedded dowels in old and new parts of specimens.

VIII. Conclusions

This research presents an investigation of shear transfer behavior of non-Coarse aggregate polymer concrete using both experimental and finite element model developed by ABAQUS software program. Based on the results obtained from Experimental and FEM, the next conclusions observed:

- The results obtained from FEM model had good agreement with experimental results and the model can be used for investigation the shear transfer behavior of both normal and polymer concrete push-off test.
- Ultimate shear strength for polymer concrete is nearly equal to the 55% of the corresponding ultimate shear strength of normal concrete due to the absence of coarse aggregate, it is recommended to use a reduction factor for the polymer concrete type in both ACI and ECC formulas when it is used to estimate the interface shear stress
- Roughening the interface lead to increase the ultimate shear strength of polymer concrete specimen.
- Treatment the interface with binding material had insignificantly effect on ultimate shear strength of polymer concrete.
- Using embedded dowels for interface connecting led to increase both the ultimate shear strength and ductility, and dowels is highly recommended for interface connection.
- Both ACI and EC codes can be used for estimating the ultimate shear strength with a reduction factor for polymer concrete.

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