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EXPERIMENTAL BOND FORCE-SLIP RELATIONSHIPS FOR EPOXY-COATED REINFORCING BARS UNDER ELEVATED TEMPERATURE CONDITIONS

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ABSRACT:- This paper presents an experimental investigation that reveals bond force - slip relationships for epoxy-coated reinforcing bars under elevated temperature conditions. The obtained experimental results indicated that coating reinforcing bars with epoxy tends to degrade the residual bond strength at elevated temperatures.

Keyword: bond, epoxy, bond-slip, slip, high temperature.

1. INTRODUCTION

In recent years, interest in special effects on structural behavior of bonded composite sections was diversified in many directions. Some researchers investigated bonding properties and others investigated the stability of these properties under variation of structural parameters or parameters of the environment like temperature. A sampling of the many research works on those directions is in order.

Using epoxy adhesives modified with liquid rubber of different content to bond the carbon fiber reinforced plastic (CFRP) strips, and four point bending experiments were carried out on RC beams. The experimental results show that different CFRP strip thickness of 0.22 and 0.44 mm resulted in a transition of failure mechanism from interfacial debonding along the CFRP-concrete interface to concrete cover separation starting from the end of CFRP strips in the concrete. Moreover, their experimental findings suggested that no matter interfacial debonding or concrete cover separation, the rubber modifier enhanced the structural performance by increasing the maximum load-carrying capacity and the corresponding ductility, compared with the beams bonded with a neat epoxy resin(1). Shear deficiency of existing members is another problem that was tackled using epoxy-based treatment methods as exemplified by some researchers who presented test results on strengthening shear deficient reinforced concrete beams by external bonding of steel plates. They tested eleven reinforced concrete beams with a T-section under monotonic loading. Three main types of steel members with different arrangements were bonded to the side of the beam webs along the shear span by using epoxy. Their purpose was to obtain ductile behavior for shear deficient reinforced concrete beams. Their test result confirmed that all steel plate arrangements improved the strength and stiffness of the specimens significantly (2).

In an important modeling-experimentation some researchers developed a 3D model to predict the behavior of carbon fiber reinforced polymer (CFRP) concrete composites under fire. They employed heat transfer analysis to predict the temperature within the adhesive layer of epoxy; which, they affirmed, the most critical part of the member at high temperature. Their model showed that the epoxy reached the failure point within a short time under standard fire. They also used the model to predict the required insulation thickness requirement for two-hour and three-hour fire resistance levels. They demonstrated the effects of rate of temperature increase on bond strength of composite structures through numerical analysis (3).

In an example of significant strength gains by epoxy treatments, a research work tested and analyzed a total of eight RC beams; one control beam and seven beams reinforced with three to six layers of carbon fiber sheets bonded by an inorganic epoxy. All specimens were subjected to a four-point bending test under load control while load, deflection, mid-span strain and failure mode were recorded up to failure. They found that the load carrying capacity increases with the number of layers of carbon fiber sheet up to 170.2% of the control beam strength. For three and four layers of FRP reinforcement, the beams failed by rupture of FRP, while beams with five and six layers of FRP reinforcement failed by FRP delamination (4).

Some papers investigated the relationship between the bond strength and the reinforcement corrosion in reinforced concrete. They proposed analytical and empirical models for the bond strength of corroded reinforcing bars. They also estimated various parameters in their analytical model. These parameters include corrosion pressure due to expansive action of corrosion products, modeling of tensile behavior of cracked concrete and adhesion and friction coefficient between the corroded bar and cracked concrete(5).

On the other hand an experimented with the mechanical behavior of bonded steel-concrete composite structures had been presented (6). The steel girder and the concrete slab were assembled by adhesives in their work. The effect of the main parameters, such as the adhesive nature and the irregular thickness of the adhesive joint, on mechanical performance and ultimate load were studied. Two adhesives were used by those authors. The results show that the connection between the steel girder and the concrete slab ensured by epoxy adhesive is perfect and without any slip in the steel-concrete interface(6).

Another papers investigated bonding connection in steel-concrete composite beams in the case of static loading and high-strength concrete. They noticed that the 3-point bending test they performed on a large beam confirms that bonding was very efficient: the elastic domain was followed by a non-linear behavior with noticeable ductility. Their measurements were generally close to the numerical results provided by beam models or the FE model. Those authors contended that the composite beam model which does not take into account slip and shear deflection could be used, however, for engineering design purposes(7).

Some other paper performed two 3-point bending tests on 4 meter span steel-concrete epoxy bonded beams which confirmed that bonding could be very efficient allowing a large plastic strain without any shear failure if the bonding joint is properly designed. The measurements conducted by those authors were close to the numerical results provided by non-linear beam models or non-linear FE model.

In the present paper, residual bond strength emerges as a variable which indicates that the structural performance of epoxy-coated reinforcing bars degrades at elevated temperatures (8).

2. TEST PROGRAM

The test program consisted of fabricating and testing 12 pull-out specimens (see Table (1)). A single concrete mix proportion (cement: fine aggregate: course aggregate) of (1:1.5:3) by weight with water/cement ratio 0.45 was used. The specimens were heated to two stages of temperature (150 C^o and 400 C^o) in addition to room temperature.

The variables investigated in the present work using pull-out specimens were the presence or absence of epoxy cover along with temperature change. The embedment length was $3d_b$.

3. FABRICATION AND DETAIL SPECIMENS

In this study, cylinder pull-out specimens were chosen. The cylinder dimensions were varied in accordance with the bar diameter. The cylinder diameter was about eight times the bar diameter ($D=8d_b$), as described in Figure (1) [9]. The cylinder dimensions were (150 × 300 mm) for a 20 mm bar diameter. The specimens were reinforced by single central reinforcing bar, with a bonded length $3d_b$. The unbounded zone is obtained by covering the reinforcing bar at this zone with a plastic tube. The steel bars were screwed from the two ends. The bottom end of the bar was screwed to be smaller in diameter than the original bar diameter, so it could fit the mold base hole and pass through it. Then the bar was fixed to the outside face of this base by a bolt, so that the bar could stand vertical at the center of the cylinder. Plate (1) shows the reinforcing bar details.

4. MATERIALS

4.1 CEMENT

Ordinary Portland cement (type I) was used in this study. The cement is manufactured in Kubaisa factory according to the Iraqi standard specification IQS 5:1984(74) requirements. The chemical and physical properties are shown in Table (2).

4.2 FINE AGREGATE

Fine aggregate obtained from Rahhalia (Anbar) region was used. The grading of the fine aggregate is shown in Table (3), and conformed to the requirements I.Q.S: 45/1985 (75).

4.3 COARSE AGREGATE

The coarse aggregate is crushed river gravel from Samara region with a maximum size of 19 mm. The coarse aggregate is washed. The aggregate is used in saturated surface dry condition. Gradation of coarse aggregate conforms to requirements of IQS: (75), as shown in Table (4).

4.4 REINFORCING STEEL

Deformed steel bars of (20 mm) were used, with yield strength of (556). Table (5) describes the reinforcing steel bars properties.

4.5. EPOXY RESIN BONDING AGENT

The commercial product Sikadur 32 is used in this study which is provides a bond of far greater strength than the tensile strength of the concrete itself. Therefore it is suitable for use wherever structural bonding of new to existing concrete is carried out. The most important physical properties are can be summarized in table (6).

5. CURING CONDITIONS

All specimens were demolded 24 hours after the casting and placed in a water tank. After 14 days of water curing, the samples were transferred to an environmental chamber. The specimens were kept in the chamber for 14 days until heating began.

6. HEATING COOLING

The specimens were heated by an electric oven; see Plate (2). The oven internal dimensions were (500×600×750 mm). The specimens were heated slowly at a constant heating rate of 2 C^o/min to avoid steep thermal gradient.

Once the required temperature level was attained, the specimens were thermally saturated for one hour at that level. Then the oven was switched off and the air-cooling was switched on. The specimens were left inside the furnace for about 3 hours and then they were moved out from the oven. Then, the specimens were stored in the laboratory environment to be cooled in air for about 20 hours.

7. TEST PROCEDURE

The pull-out specimens were tested by applying a tensile force to the steel bar while the concrete cylinder bore against the platen of the testing machine. The slip of the bar at the free end was measured by dial gage see Figure (2) and Plate (3). The specimens were tested up to the maximum possible load was reached.

8. TEST RESULTS

It is noticed that the splitting failure is the common type of failure observed in this study.

Figures 3-8 present relationships between bond force for bars coated with epoxy or without epoxy and free end slip, under elevated temperature starting from room temperature to 400 C^{o}. Those curves show that there is a difference in the slip increase with temperature that appeared consistently at all temperatures. As the load increases the slip increases in a faster rate (upon temperature increase) until the bond breaks down and failure occurs.

The results summarized graphically in Figures (9) and (10) show that the residual bond strength degraded as the exposure temperature was increased. The results show that the use of epoxy coating on the bars at high temperature resulted in the residual bond strength being less than that for bars without epoxy-coating. The residual bond strength for epoxy-coated bars was 67% while residual bond strength for bars without epoxy-coating was 77%, as shown in Figure (11).

9. CONCLUSIONS

The following conclusions may be drawn from the work

1. There is a difference in the slip increase with temperature that appeared consistently at all temperatures. As the load increases the slip increases in a faster rate (upon temperature increase) until the bond breaks down and failure occurs.
2. The obtained experimental results indicated that coating reinforcing bars with epoxy tends to degrade the residual bond strength at elevated temperatures. Where the residual bond strength for epoxy-coated bars was 67% while residual bond strength for bars without epoxy-coating was 77%.
3. At high temperature, the bond stress-slip curve is of a flatter slope than that at room temperature. Moreover, at temperature about 400C^{o} and above, the adhesion bond seems to disappear.
4. Bond strength is affected when exposed to high temperature, depending on level of temperature.
5. The bond stress behavior at elevated temperature is noticed to be of the same order as the behavior of concrete compressive strength.

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Table (1): descriptions of classification of pull- out specimens.

	No. of pull-out specimens		
Embedded Bars description	**At Room Temp.**	**At Temp. 150 C^o**	**At Temp. 400 C^o**
Embedded bars without coated by epoxy	**(2) specimens**	**(2) specimens**	**(2) specimens**
Embedded bars coated by epoxy	**(2) specimens**	**(2) specimens**	**(2) specimens**

Table (2A): Chemical composite of cement#.

NO.	Chemical composite	Project cement percent	IQS:NO./1984
1	CaO	61.54	
2	SiO_2	21.7	
3	Al_2O_3	5.3	
4	Fe_2O_3	3.18	
5	MgO	2.71	5*
6	SO_3	2.46	2.8*
7	L.O.I	2.2	4.0*
8	Insoluble Residue	0.5	1.5*
9	L.S.F	0.68	0.66 – 1.02
10	C_3A	8.66	
11	C_3S	38.38	
12	C_2S	31.59	
13	C4AF	8.87	

Table (2B): Physical properties of the cement#.

Physical properties	Test result	IQS:No.5l1984
Fine using Blain air Permeability apparatus (cm^2/gm)	4000	2300**
Sound using Autoclave method	0.17	0.8*%
Setting time using vicat's Instruments Initial (min) Final(min)	 150 225	 45** 600*
Compressive strength for Cement past cube (70.7 mm) at 3 days(MPa) 7 days(MPa) 28 days(MPa) 56 days(MPa)	 22.1 32.3 41.2 59.8	 15** 23** …. ….

All testing were made at Al-Mustansirya University Laboratories.
*Maximum Limit.
**Minimum Limit.

Table (3): Grading of fine aggregate#.

No.	Sieve (mm)	%Passing	
		Fine aggregate	IQS 45:1984
1	5.0	97	90 – 100
2	2.36	78	75 – 100
3	1.18	60	55 – 90
4	0.60	43.7	35 – 59
5	0.30	17.5	8 – 30
6	0.15	0	0 - 10

#All tests were made at Al-Mustansirya University Laboratories

Table (4): Grading of coarse aggregate#.

No.	Sieve (mm)	%Passing	
		Coarse Aggregate%	IQS 45:1984
1	20	100	100
2	14	99	90-100
3	10	57	50-85
4	5	0-10	4.5
5	2.36	0	-

#All tests were made at Al-Mustansirya University Laboratories

Table (5): Properties of reinforcement steel#.

Approximate Diameter (mm)	Measured Diameter (mm)	Area (mm^2)	Modulus Elasticity (GPa)	*fy* MPa	*fu* MPa
20	19.62	314	200	556	705

#All tests were made at Al-Mustansirya University Laboratories

Table (6): Mechanical strengths of epoxy#.

Density Kg/lt	Compressive strength(N/ mm^2)	Flexural strength(N/ mm^2)	Tensile strength (N/ mm^2)
1.4	60-70	30-35	18-20

Product data sheet of epoxy resin bonding agent “Sikadur-32”

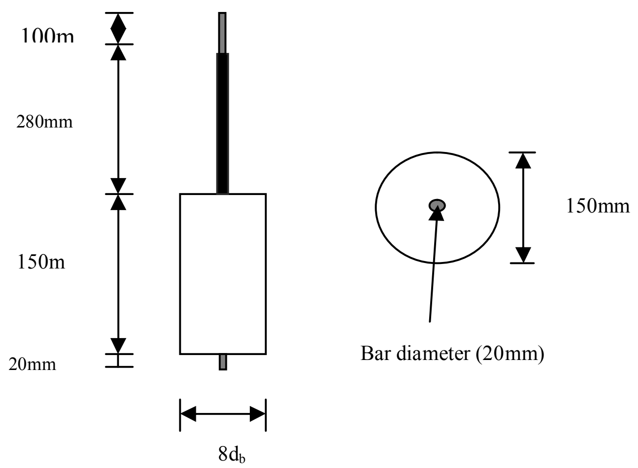


Fig.(1): Test specimen details.

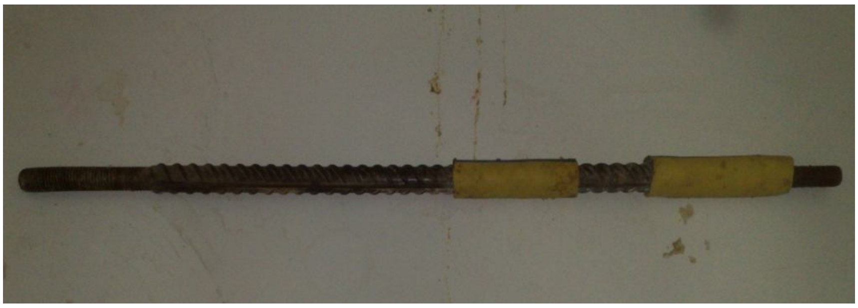
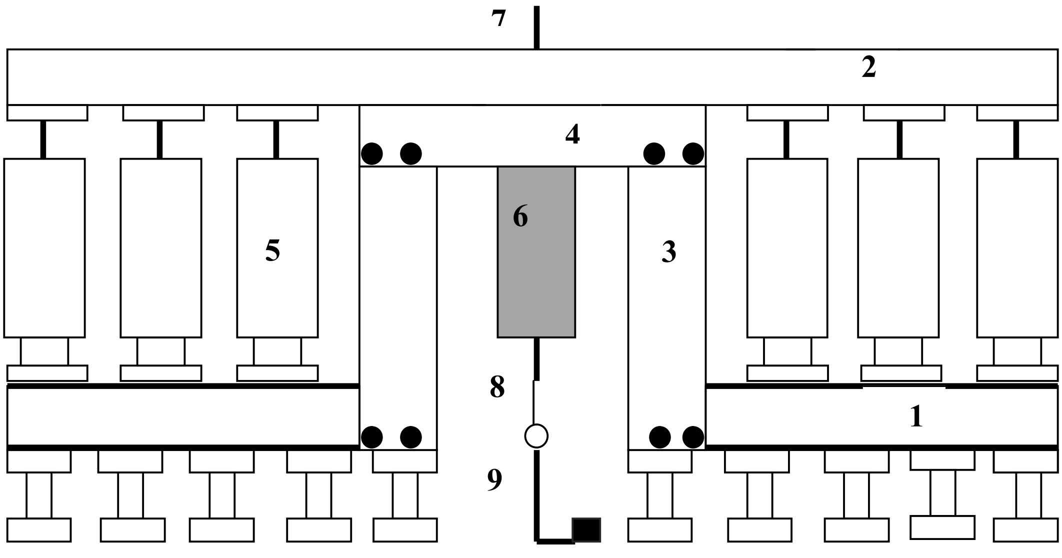


Plate (1): Steel bar details**.**

Plate (2): The used oven.



1-Fixed Head
2-Moving Head
3-Standing Section
4-Bearing Plate
5-Hydraulic Jack
6-Concrete Cylinder
7-Bar Loaded End
8-Bar Unloaded End
9-Dial Gage

Fig.(2): Details of testing frame.

Plate (3): Hydraulic Loading Machine.

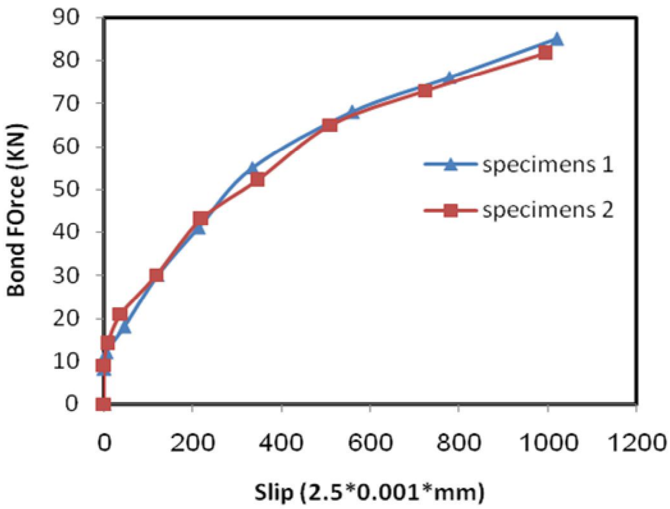


Fig.(3): Bond force-slip relationship for epoxy-coated bar specimens at room temperature.

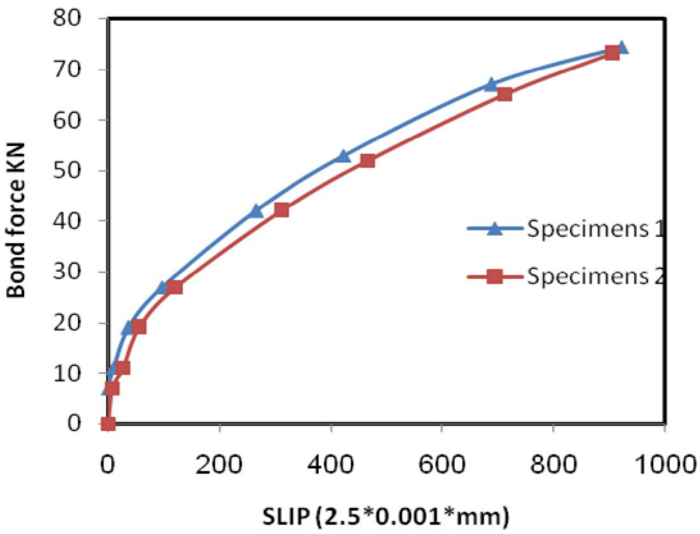


Fig.(4): Bond force-slip relationship for uncoated bar specimens at room temperature.

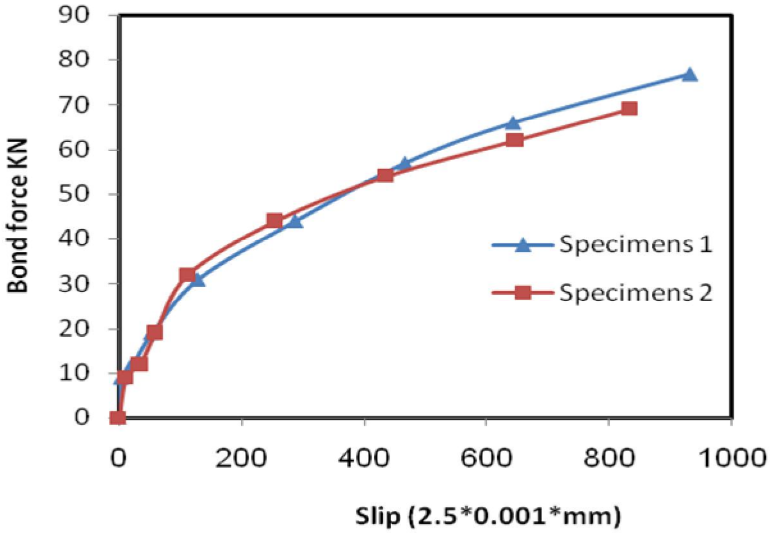


Fig.(5): Bond force-slip relationship for epoxy-coated bar specimens at 150 C^o.

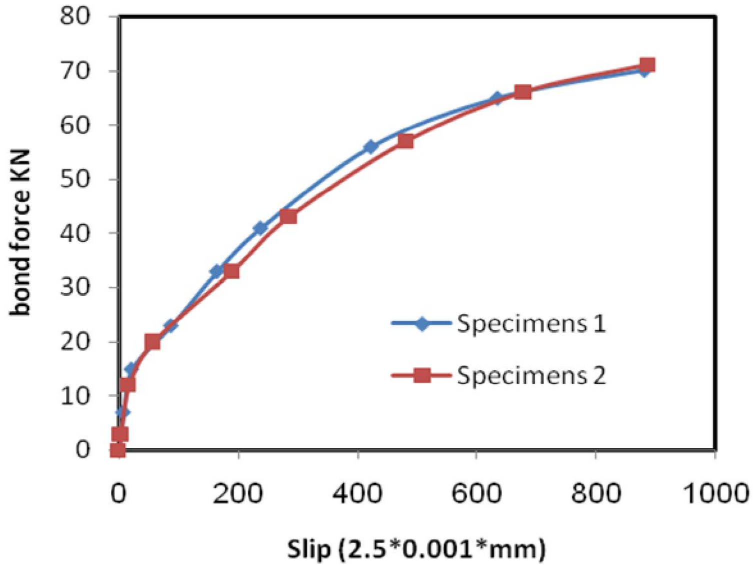


Fig.(6): Bond force-slip relationship for uncoated bar specimens at 150 C^o.

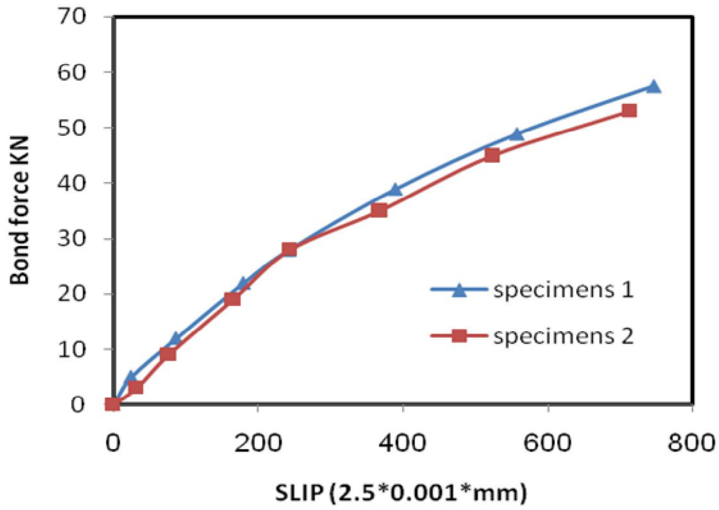


Fig.(7): Bond force-slip relationship for epoxy-coated bar specimens at 400 C^o.

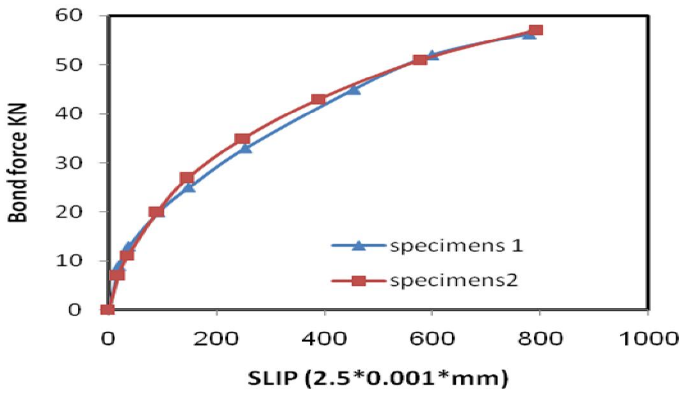


Fig.(8). Bond force-slip relationship for uncoated bar specimens at 400 C^o**.**

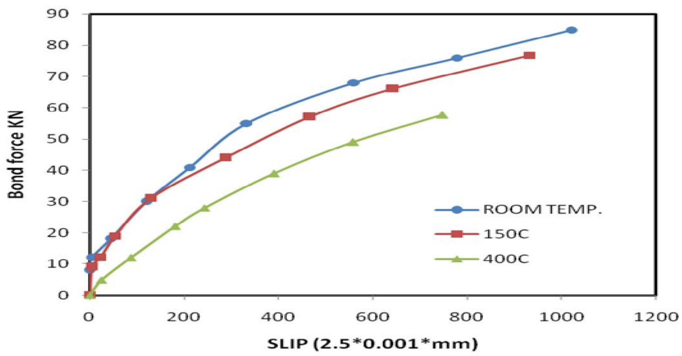


Fig.(9): Bond force-slip relationship for epoxy-coated bar specimens at various temperatures.

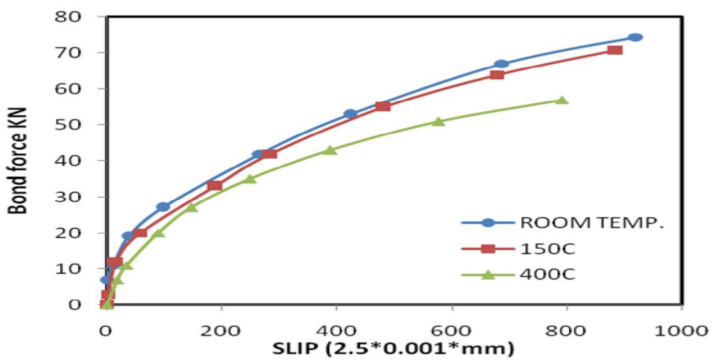


Fig.(10): Bond force-slip relationship for uncoated bar specimens at various temperatures.

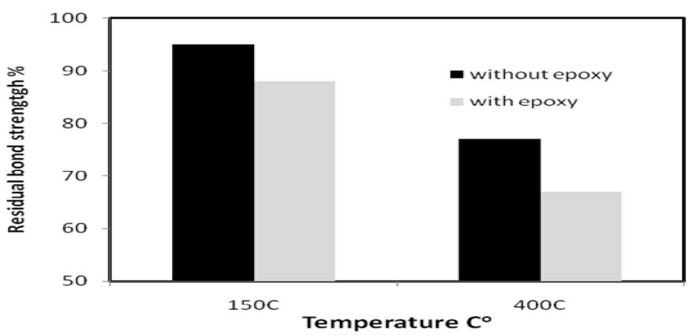


Fig.(11): Variation of percentage residual bond strength with temperature for epoxy-coated and uncoated bar specimens.

دراسة تجريبية لعلاقات قوةالربط–الانزلاق لقضبان التسليح المغطاة بالايبوكسي في درجات الحرارة العالية

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الخلاصة

هذه الدراسة تقدم بحثا تجريبيا لاختبار تاثر مادة الايبوكسي على قوة الربط بين الكونكريت وحديد التسليح ومدى تأثرها عند رفع درجه الحرارةوذلك بتسخين النماذج بواسطة الافران ثم اعادة تبريدها وفق قيم درجات الحرارة المعتمدة في هذه الدراسة وكما هو مبين في برنامج الاختبار. من خلال النتائج التي تم الحصول عليها تبين ان طلاء حديد بالايبوكسي يسبب تدهور في قوة الربط بين الكونكريت وحديد التسليح وذلك في درجات الحرارة العالية.