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Original article

Pull-out behavior of post installed rebar connections using chemical adhesives and cement based binders

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ABSTRACT

This study investigated the effectiveness of several types of adhesives used in post-installed rebar connections as a bonding agent between steel reinforcement bars and old concrete under pull-out test. The cylindrical samples (96 + 24 Nos) of 15 dia. × 30 cm with anchors rebar of varying diameter (8, 10, 12 mm) with different embedded length (10, 15 and 20 × rebar diameter). The control (24 Nos) was the cast in-place rebar concrete specimens while other samples (96 Nos) were post rebar-installed concrete specimen of varied bonding agents-chemical adhesives (*Sikadure-31CF* and *EPICHOR 1786*) or cement-based binders (mortar, ultra-high performance self-compacting concrete (UHPSCC). The findings showed that the use of the adhesives and UHPCC pull-out load values were in close proximity while they all outperformed mortar bonded specimens. The pull-out load (bond strength) increases with the embedded length and the diameter of the rebar. Failure mode of post installed rebar concrete is governed by the embedded length and the area of contact with the adhesives or binder. Larger diameter of rebar favours splitting or failure of concrete due to higher strength in binder-rebar interface compare to binder-concrete interface.

1. Introduction

Anchors that are used to provide connections between different structural members and concrete can be presented in two categories; such as cast-in-place and post-installed in concrete type (Cook, 1993; Looney et al., 2012; Wang et al., 2016). Post installed reinforcement is installed into a hardened concrete member by drilling holes and inserting the bar with binders or adhesives. This method is used for different purposes such as binding new concrete to the old or pre-existing one, This enables continuity, strengthening or homogenous stress transfer in the structures by means of additional reinforcing or transferent bars. Such bars are typically glue or mortar bonded in a pre-drilled hole (Randl, 2011; Soudki et al., 2012; Brencich, 2015). It is known that transfer of load or stress in reinforced concrete is based on the bond between the reinforcing steel and the surrounding concrete or binders (Çalışkan et al., 2013; Kim et al., 2013). This transfer is provided by the resistance to relative motion or slippage between the concrete and the rib faces of embedded steel bar. The resistance to slippage is alternatively known as the bond strength which depends on three actions: (1) chemical adhesion; (2) friction; (3) mechanical interaction between the ribs of the bar and the surrounding concrete (ACI-408R, 2003; NCHRP, 2009; Lu et al., 2016).

Understanding anchor behavior is necessary to specify the appropriate anchorage for a given application. This includes failure modes, strengths, load displacement and relaxation characteristics of various anchor types (ACI-355, 1991). It also requires an in-depth understanding of the physical phenomena involved in the complete process of setting and loading in concrete (Li et al., 2005). Anchors are loaded through tension, shear or combinations of both in the embedded anchor. Anchors may also be subjected to bending depending on the shear transfer through attachments. This is very common in dynamic loading which may occur in pipelines, bridges, railway barriers and machine foundations. Fatigue and seismic loads may also act on anchorage systems (Maziligüney, 2007).

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The adhesive anchors can develop the required strength in a shallow depth as compared to the normal concrete required rebar development length. The adhesive anchor generally consists of a reinforcing bar inserted into a drilled hole in hardened concrete with a structural adhesive, which could be mortal or chemicals (Cook, 1992, 1993; Çolak, 2001; Cook and Konz, 2001). The post-installed anchors can be driven in hardened concrete and bonded with the aid of chemical adhesive or cement binders (Shah et al., 2012; Yilmaz et al., 2013). Cleanness of hole, drilling method, humidity level of concrete, environment temperature and many other parameters like adhesive material type and microstructural properties can affect bond strength of anchors (Eligehausen et al., 2006).

Furthermore, the adhesive geometrical properties like the thickness of additives (Çolak, 2001), anchorage bar diameter (Gesoglu et al., 2005), embedment depth (McVay et al., 1996), steel strength (Cook, 1992), free edge distance (Obata et al., 1998) can affect the performance of anchorage or bond strength of anchors. Some other studies (Eligehausen et al., 2006) investigated the behavior of both single and group anchors, likewise, the effect of concrete strength and aggregate variety (Cook and Konz, 2001; Tayeh et al., 2012a,b). In addition, some studies also focus on the increase in tensile strength related to the increase in loading pace rate under dynamic loads (Fujikake et al., 2003).

Post-installed rebars are widely used in Gaza Strip because of the need for it in rehabilitation and strengthening works. The efficiency of the adhesive materials available at the local markets has never been verified. The aim of this study is to investigate the efficacy of anchor through pull-out test of different types of adhesives and cement based binders as being used in construction industry. In addition, the contribution of development lengths as affected the pull-out loads in post-installed rebar and cast in-place rebar concrete specimens were also evaluated. This research will contribute to the efficiency in the cost of construction in general, and provide a level of confidence on the structural integrity of building and civil engineering infrastructural projects in Gaza strip on the occasion of in-construction design modification, terotechnology and retrofitting.

2. Experimental program

2.1. Materials

2.1.1. Cement

The cement used, in this research, is Portland cement "EN 197-1-cem 1 (42.5 N) type 1. Table 1 summarized the cement properties.

2.1.2. Reinforcing steel bars

The reinforcement bars used in this research are 12 mm, 10 mm and 8 mm in diameter. The properties of these bars as shown in Table 2:

Table 1
Properties of cement.

Description	Sample Results	EN-197 spec.
Normal consistency Setting time	26.5%	
1- Initial sitting (min)	95	
2- Final sitting (min)	185	
Compressive strength (MPa)	18.4	Min 10
1- 2 days	37.0	
2- 3 days	48.6	Min 42.5,
3- 28 days		max 62.5

Table 2
Properties of steel reinforcement.

Diameter (mm)	Yield strength (MPa)	Ultimate strength (MPa)
Ø12	466.9	621.0
Ø10	421.0	493.0
Ø8	492.8	691.5

2.1.3. Concrete

The target compressive strength of the concrete used in this research at 28 days was 25 MPa. The required amounts of all constituent materials were weighed properly according to the contents with cement content of 325 kg/m^3, w/c of 0.53. The aggregates used were crushed coarse limestone aggregate of maximum size ¾ inch with the proportion of 100 kg/m^3. The fine aggregate or sand was sand was 730 kg/cm^3.

2.1.4. Adhesives

Four types of adhesives are used for post–installed reinforcement bars.

2.1.4.1. EPICHOR 1768. This adhesive consists of two components; one is the resin and the other is the hardener. In order to prepare the mix, fine sand is added to the resin where the ratio of the (resin + hardener) to fine sand is 1:4. The resin, the hardener and the fine sand are mixed according to the manufacturer's recommendations. Properties of the adhesive are shown in Table 3.

2.1.4.2. Sikadure – 31 CF. Sikadure – 31CF is a solvent free thyrotrophic which consists of two components, based on a combination of epoxy resins and pecially selected high strength fillers. Table 4 shows the properties of *Sikadure – 31CF.*

2.1.4.3. Ultra-high performance self-compacting concrete (UHPSCC). UHPSCC is mixed according to the quality listed in Table 5 and prepared with w/c ratio of 0.24.

2.1.4.4. Mortar. The mortar is prepared with water to cement ratio of 0.5 with equal weights of cement and sand.

Table 3
Properties of EPICHOR 1768.

Description	Sample Results
Compressive strength	
After 7 days	42 N/mm^2
After 24 days	67 N/mm^2
Tensile strength (after 7 days)	2.9 N/mm^2
Flexural strength (after 7 days)	54 N/mm^2
Time after mixing	20 min in 24 °C

Table 4
Properties of Sikadure – 31CF.

Description	Sample Results After 10 days (MPa)
Compressive strength	
After 24 h at 20 °C	60–70
After 24 h at 30 °C	40–45
After 24 h at 50 °C	35–40
Tensile strength	15–20
Flexural strength	30–40
Bond strength to concrete	3.5
Bond strength to steel	15
Time after mixing	40 min in 20 °C
	20 min in 30 °C

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Table 5
Components of UHPFRSCC mixture (Al Madhoun, 2013).

Materials	Proportion (kg/m^3)
Cement CEM I 42.5R	900
Water	216
Silica fume	135
Quartz sand	1125
Superplasticizer	27

2.2. Sample size and description

The experimental program consists of pull-out test which examines the strength of the adhesives that bond rebars to the concrete in post-installed rebar connections with the concrete. The concrete cylinders (3 × 8 + 3 × 24 Nos) of size 15 cm diameter (Ø) and 30 cm height were used for post installed rebar concrete while (3 × 8 Nos) were used for cast in place control samples (Assaad and Issa, 2012; Shah et al., 2012; Yoo et al., 2015). For 96 post installed rebar concrete specimens, the hardened concrete samples were drilled and rebars of different diameters (8 mm, 10 mm and 12 mm) with the embedded length of 10, 15 and 20 with rebar diameter (10Ø, 15Ø and 20Ø). The bonding was achieved by adhesives (*Sikadure – 31CF and EPICHOR 1768*), mortar and UHPSCC concrete. The 24 control samples were cast in place with similar variation in rebar diameter and the embedded lengths which varied as before described. Fig. 1 shows the experimental program flowchart.

The pull-out value recorded was the average of three replica values. The results are designated as F_{xpya} and F_{xcya} for post-installed rebar (p) and cast in place specimens (c), respectively. 'F' is the recorded pull-out load values, 'x' is the rebar diameter of embedded length (y which could be 10, 15 or 20 times x).

The adhesives is represented as 'a' representing E,S,M,U (*EPICHOR 1768* (E), *Sikadure-31CF* (S), mortar (M) or UHPSCC (U)). For instance, F_{8p10E} could be described as the pull-out load value for 8 mm Ø post-installed rebar with embedment length of 10 times rebar diameter, 10Ø (8 cm), and bonded by *EPICHOR 1768*.

2.3. Mixing, casting and curing procedures

The concrete constituent materials were proportioned and weighed properly and then mixed in a rotary mixer. The fresh concrete was cast in three equal layers in 15 cm by 30 cm cylindrical forms. The curing process was done according to ASTM C192 (ASTM, 1998). The sample was demoulded after 24 h and then

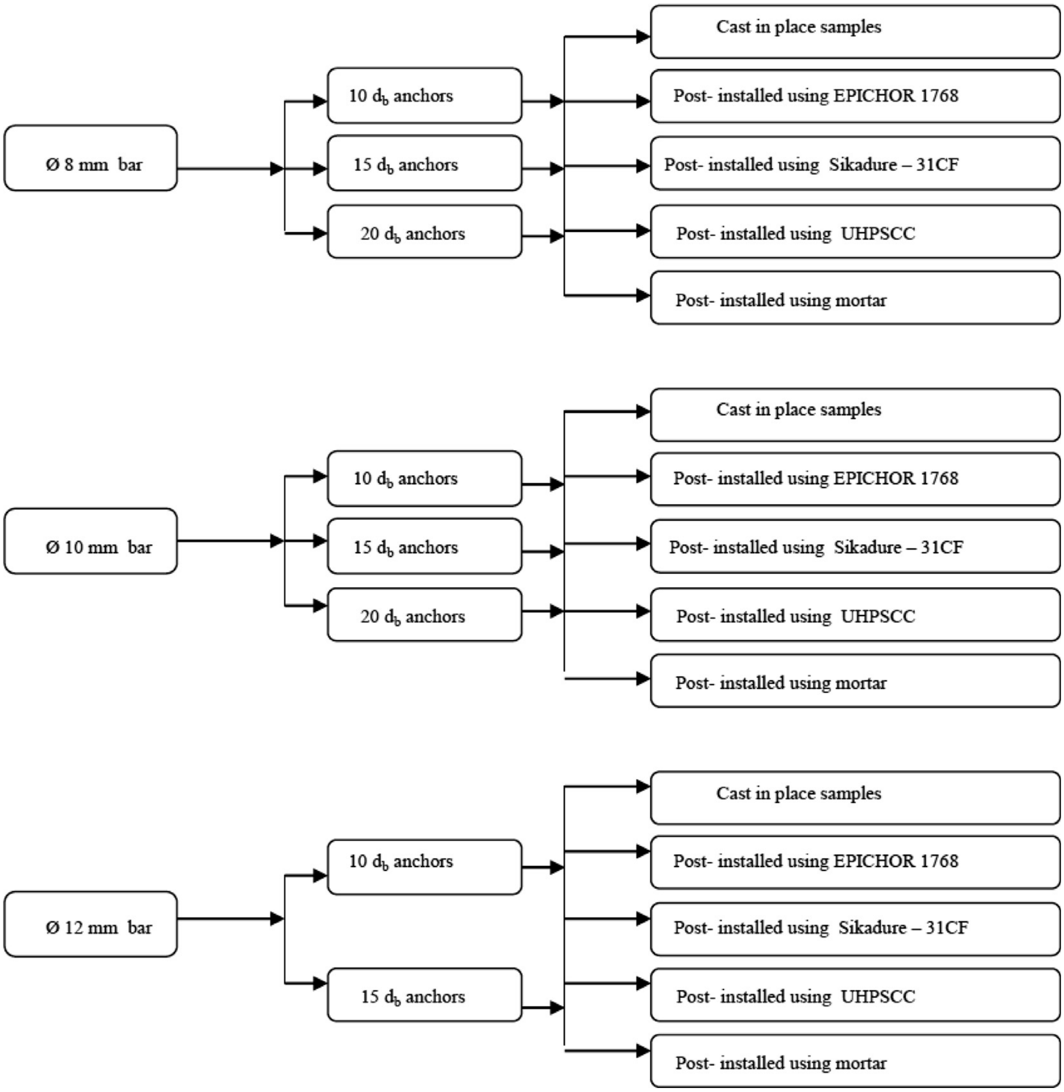

Fig. 1. Experimental program flowchart.

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cured by water ponding for 1 week. Upon the removal, the specimens were left in the open air for three more weeks to dry before drilling operation was conducted. In this research, the anchorage lengths or embedment depths used were 10, 15 and 20 times the anchor diameter.

2.3.1. Drilling and cleaning of the holes

Holes were drilled in the post-rebar concrete using a vibrating rotary hammer drill. The hole for 8 mm, 10 mm and 12 mm diameters anchors were drilled along the longitudinal axes of the specimens with a 12 mm, 15 mm and 18 mm diameter diamond bits, respectively. The compressed air was used to remove all the loose concrete particles that could affect proper bonding of the rebar with the concrete. Water jet was later used for further cleaning while the samples were left to dry out (2, 1992; Shah et al., 2012), as shown in Fig. 2.

2.3.1.1. Preparing and injecting the adhesives. All types of adhesives are mixed according to the manufacturer's recommendations. While the mortar is prepared with cement to sand weight ratio of 1:1. The injections of the adhesives into the samples were done by using empty silicon containers 'gun' filled with the needed amounts of the adhesives and then applied into the drilled holes together with rebars.

2.3.2. Inserting of the anchors

The anchors were also marked for embedment depths before installation. After filling two – thirds of the hole length by the adhesive using the silicon gun, the anchors are also brushed with the adhesive before being inserted into the holes by twisting them slowly inwardly. The excess adhesive around the holes was then cleaned for neatness (Shah et al., 2012). In this procedure, it can be guaranteed that the whole pore volume between the anchor and the surfaces of the holes were filled up completely. According to ACI Code 318-14, the development length to bar diameter ratio L_d / d_b is given by:

$$L_d = \left(\frac{f_y\psi_t\psi_e\psi_s}{3.5\lambda\left(\frac{c_b+K_{tr}}{d_b}\right)\sqrt{f'c}}\right)d_b$$

$$\frac{l_d}{d_b} = \frac{f_y\psi_t\psi_e\psi_s}{3.5\lambda\sqrt{\mathrm{fc}}((\mathrm{c_b}+\mathrm{K_{tr}})/\mathrm{d_b})} = \frac{4200(1)(1)(0.8)}{3.5(2.5)\sqrt{250}} = 24.29cm$$

while f_y = 420 MPa for steel bar Φ10 mm and Φ12 mm, and $f_{c'}$ for cylindrical sample.

L_d development length cm.
D_p nominal diameter of bar cm.
F_y Specified yield strength of reinforcement kg/cm^2.
$\sqrt{f}_c$ Square root of specified compressive strength of concrete kg/cm^2.
C_d Spacing or cover dimension, cm.
ψ_s Factor used to modify development length based on reinforcement size.
ψ_t Factor used to modify development length based on reinforcement location.
ψ_e Factor used to modify development length based on reinforcement coating.
λ Lightweight aggregate concrete factor.

where:

For Φ8mm, L_d = 24.29 * (0.8) ≈ 20 cm
For Φ10mm, L_d = 24.29 * (1.0) ≈ 25 cm
For Φ12mm, L_d = 24.29 * (1.2) ≈ 30 cm

Fig. 2. Cleaning of the drilled holes.

Fig. 3. Pull-out testing machine.

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2.3.3. Pull-out test

The embedded lengths, the type of adhesive and date of casting are also recorded on the concrete samples. Pull-out tests started at least 36 h (1.5 days) after the placement of the anchors using *EPICHOR 1768* and *Sikadure – 31CF* adhesives. The test was conducted after 14 days of installation of the anchors. The load was applied to the anchors at the loading rate 20 kN/min (Fig. 3) until reaching the maximum failing load. A load cell was attached to the system to record the failure loads for each rebar diameter of different adhesives and the embedded lengths.

3. Results and discussion

3.1. Pull-out loads and failure modes for 12 mm diameter rebars

3.1.1. Pull-out loads of Ø12 mm bars

The results listed in Table 6 and Fig. 4 show that the average pull-out load of 12 mm rebars in post-installed rebar samples using *Sikadure – 31CF* adhesive with embedment length of 10Ø (F_{12p10S}) and 15Ø (F_{12p15S}) were about 82% and 100%, respectively of the cast in place pull-out load (F_{12c10S} and F_{12c10S}).

The average pull-out loads of Ø12 bars in post-installed rebar samples using *EPICHOR 1768* adhesive with embedment length of 10Ø (F_{12p10E}) and 15Ø (F_{12p15E}) were about 96% and 100% of the cast in place pull-out load. The use of UHPSCC reduced the pull-out load values of F_{12p10U} and F_{12p15U} to about 69% and 96% of the cast in place pull-out loads (F_{12c10U} and F_{12c15U}). It also had the lowest value for embedded length of 10Ø among the other binders. Though, as the embedded length increased to 15Ø, UHPSCC sample outperformed mortar binder samples (the lowest strength) by 36% (Fig. 4).

It means that using of UHPSCC is good in long embedment lengths, though it is only sparingly better (<1%) and worse (<2%) than *EPICHOR 1768* and *Sikadure-31CF*, respectively (Tayeh et al., 2012a,b; Tayeh et al., 2013a,b; Yoo et al., 2015; Hung and Chueh, 2016). It can also be observed that the bond strength increases with the embedded length. While it (UHPCC) is less than that of *EPICHOR 1768* at the length of 10Ø by 12.8%, it becomes higher by 6.4% as the embedded length increases to 15Ø.

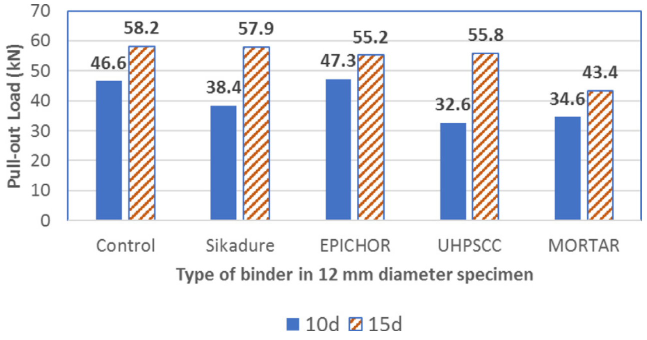

Fig. 4. Capacity of bonded Ø12 mm anchors using several types of adhesives.

3.1.2. Failure mode under pull-out load of 12 mm bars

The results shown in Fig. 5b indicates that the mode of failure for Ø12 bars either in cast in place and in post-installed rebars using chemical adhesives, and UHPSCC for embedment lengths of 10Ø and 15Ø were splitting of concrete specimens (Fig. 5b). No yielding failure of the rebar was experienced for cast in place and for post-installed rebar using adhesives. However, the mortar bonded samples failed by slippage of rebar from the concrete matrix. This implies that the bond strength between rebar-concrete interface is weaker than the yield strength of the rebars.

3.2. Pull-out loads of Ø10 mm bars

The results listed in Table 7 and Fig. 6 show that the average pull-out load of 10 mm diameter bars in post-installed rebar

Table 6
The average values of pull-out loads of Ø12 mm bars.

	Embedment length	Pull-out load (kN)	Average pull-out load(kN)	Failure mode
Control samples	10 Ø	42.7	46.6	Splitting in the concrete specimen
		NA		Splitting in the concrete specimen
		50.5		Splitting in the concrete specimen
	15 Ø	58.4	58.2	Splitting in the concrete specimen
		58		Splitting in the concrete specimen
Sikadure – 31CF samples	10 Ø	39	38.4	Splitting in the concrete specimen
		40.5		Splitting in the concrete specimen
		35.7		Splitting in the concrete specimen
	15 Ø	58.3	57.9	Splitting in the concrete specimen
		60.4		Splitting in the concrete specimen
		55		Splitting in the concrete specimen
EPICHOR samples	10 Ø	42.1	47.3	Splitting in the concrete specimen
		46.7		Splitting in the concrete specimen
		53.1		Splitting in the concrete specimen
	15 Ø	51.4	55.2	Splitting in the concrete specimen
		60.2		Splitting in the concrete specimen
		54		Splitting in the concrete specimen
UHPSCC samples	10 Ø	30.9	32.6	Splitting in the concrete specimen
		34.3		Splitting in the concrete specimen
	15 Ø	57.4	55.8	Splitting in the concrete specimen
		55		Splitting in the concrete specimen
		55.1		Splitting in the concrete specimen
Mortar samples	10 Ø	36	34.6	Slippage of the anchor
		41.9		Slippage of the anchor
		26		Splitting in the concrete specimen
	15 Ø	37.5	43.4	Splitting in the concrete specimen
		43.7		Splitting in the concrete specimen
		49		Splitting in the concrete specimen

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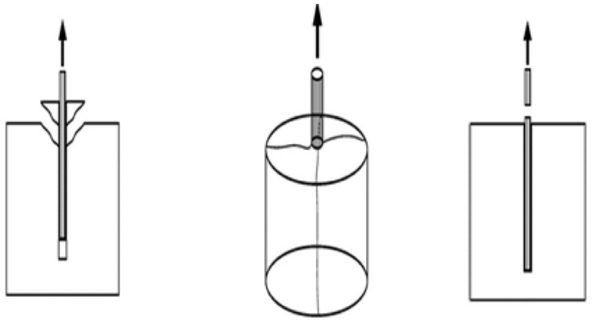

a) Combined concrete cone and bond failure **b) Concrete splitting failure** **c) Anchor rupture**

Fig. 5. Modes of failure.

samples using *Sikadure – 31CF* adhesive (F_{10pyS}) with embedment length of 10Ø, 15Ø and 20Ø (F_{10p10S}, F_{10p15S}, F_{10p20S}), were about 92%, 81% and 94% of cast in place pull-out loads (F_{10c10S}, F_{10c15S}, F_{10c20S}), respectively.

The average pull-out load of post-installed rebar specimen with embedment length of 10Ø, 15Ø and 20Ø in *EPICHOR 1768* (F_{10p10E}, F_{10p15E}, F_{10p20E}) was about 105.7%, 102.6% and 104% while UHPSCC (F_{10p10U}, F_{10p15U}, F_{10p20U}) was 97.6%, 99.1% and 104.3%, respectively of the cast in-place rebar specimens' pull-out loads. Hence, the use of *EPICHOR 1768* and UHPSCC outperformed other binders as shown in Fig. 6.

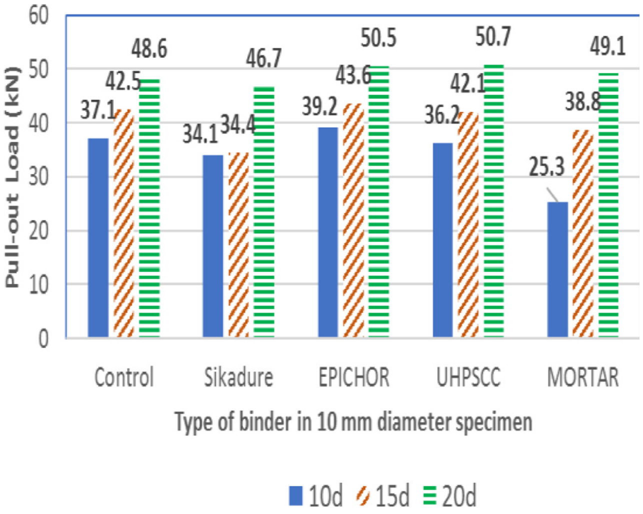

Fig. 6. Capacity of bonded Ø10 mm anchors using several types of adhesives.

The mortar binding rebar specimens for the 3 different embedded lengths have 68.2%, 91.2% and 101% of the loads recorded in cast in-place samples control. The longer the embedded length, the higher the bond stress distribution around the bar periphery and the pull-out load.

3.2.1. Failure mode under pull-out load of Ø10 mm bars

The mode of failure when using 10 mm bars either in cast in place samples or in post-installed rebar samples using adhesives

Table 7
The average values of pull-out loads of Ø10 mm bars.

	Embedment length	Pull-out load (kN)	Average pull-out load (kN)	Failure mode
Control samples	10 Ø	37.5	37.1	Splitting in the concrete specimen
		36.6		Splitting in the concrete specimen
	15 Ø	44.5	42.5	Splitting in the concrete specimen
		40.5		Splitting in the concrete specimen
	20 Ø	49.6	48.6	Splitting in the concrete specimen
		47.6		Splitting in the concrete specimen
Sikadure – 31CF samples	10 Ø	33.5	34.1	Splitting in the concrete specimen
		34.6		Splitting in the concrete specimen
	15 Ø	35.7	34.35	Splitting in the concrete specimen
		33		Splitting in the concrete specimen
	20 Ø	44.5	46.7	Yielding of the anchor followed by elongation in the bar
		50.3		Yielding of the anchor followed by elongation in the bar
		45.3		Yielding of the anchor followed by elongation in the bar
EPICHOR samples	10 Ø	42.2	39.2	Splitting in the concrete specimen
		38.5		Splitting in the concrete specimen
		37		Splitting in the concrete specimen
	15 Ø	45.8	43.6	Splitting in the concrete specimen
		40		Splitting in the concrete specimen
		44.9		Splitting in the concrete specimen
	20Ø	51.4	50.5	Yielding of the anchor followed by anchor rupture
		49.6		Splitting in the concrete specimen
UHPSCC samples	10 Ø	37	36.2	Splitting in the concrete specimen
		35.3		Splitting in the concrete specimen
	15 Ø	39.2	42.1	Splitting in the concrete specimen
		45		Splitting in the concrete specimen
	20Ø	51.1	50.7	Yielding of the anchor followed by anchor rupture
		52.4		Yielding of the anchor followed by elongation in the bar
		48.7		Splitting in the concrete specimen
Mortar samples	10 Ø	25.6	25.3	Pull-out of the Anchor
		24.9		Pull-out of the Anchor
	15Ø	40.7	38.8	Pull-out of the Anchor
		36.8		Pull-out of the Anchor
	20Ø	47.4	49.1	Pull-out of the Anchor
		48.8		Pull-out of the Anchor
		51		Pull-out of the Anchor

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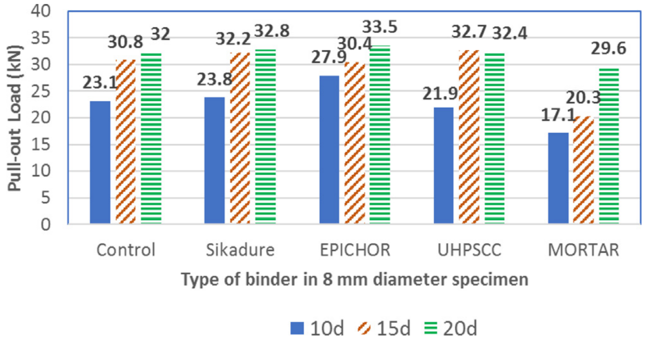

Fig. 7. Capacity of bonded Ø8 mm anchors using several types of adhesives.

with embedment lengths of 10Ø and 15Ø was also found to be longitudinal splitting of concrete specimens whenever the pull-out loads is less than 44 kN as shown in the control cast in-place specimens whereas as the embedded length increases to 20Ø (Fig. 5b) yielding of rebar characterized the failure mode as the loads exceed 46.7 kN (Fig. 5c). This is evident in the *Sikadure-31CF*, UHPSCC and *EPICHOR 1768* specimens. The yielding of 10 mm bars occurred in post-installed rebar samples with embedment length of 20Ø bonded with adhesive. This could be caused by using development length, L_d less than that required by ACI Code.

However, the relatively low strength mortar based binders resulted in the slippage of anchors (bond failure) as shown in Fig. 5a even with the embedded length to 20Ø and enhanced load value of 49.1 kN. The initiation of microcracks within the mortar matrix could inform the crack propagation within the matrix. Hence, the use of the mortar in post-installed rebars is not preferable in the presence of other alternatives like UHPSCC, *EPICHOR 1768* and *Sikadure-31CF.*

3.3. Pull-out loads of Ø8 mm bars

From Fig. 7, regardless of the development lengths used, the diameter of the rebar controls the pull-out load of the examined specimens. The average maximum load (33.5 kN) was recorded with *EPICHOR 1768* while the minimum with mortar bonded samples. The load increases as the embedded lengths increases. UHPSCC was found to be 78.5%, 107.6% and 96.7% of the values obtained in *EPICHOR 1768* samples for embedded length of 10Ø, 15Ø and 20Ø, respectively. The percentages become 85.3%, 105.9% and 97.9% upon comparing *Sikadure–31CF with EPICHOR 1768* (Fig. 7). The average F_{8p10M} was about 80% of F_{8c10U} for embedment length of 10Ø but changed to 62.1% and 91.3% as the embedded lengths increased to 15Ø and 20Ø, respectively. F_{8p10U}, F_{8p15U}, and F_{8p20U} are 94.8%, 106.2%, 101.3% of the cast in-place control sample but upon comparing the control samples with mortar bonded specimens the values (F_{8p10M}, F_{8p15M}, and F_{8p20M}) change to 74%, 65.9% and 92.5%, respectively.

Table 8
The average values of pull-out loads of Ø8 mm bars.

	Embedment length	Pull-out load (kN)	Average pull-out load (kN)	Failure mode
Control samples	10 Ø	22.5	23.1	Pull-out of the Anchor
		23.7		Pull-out of the Anchor
	15 Ø	30.9	30.8	Pull-out of the Anchor
		30.7		Pull-out of the Anchor
	20 Ø	32.5	32	Yielding of the anchor followed by bond failure
		31.5		Yielding of the anchor followed by bond failure
Sikadure – 31CF samples	10 Ø	23	23.8	Splitting in the concrete specimen
		23.7		Splitting in the concrete specimen
		24.8		Splitting in the concrete specimen
	15 Ø	30.8	32.2	Pull out, combined cone failure
		31.5		Pull out, combined cone failure
		32		Pull out, combined cone failure
	20 Ø	33	32.8	Pull-out of the Anchor
		33.6		Pull out, combined cone failure
		31.9		Pull-out of the Anchor
EPICHOR samples	10 Ø	26.9	27.9	Pull out of the anchor + concrete failure
		29		Yielding of the anchor followed by anchor rupture
	15 Ø	31	30.4	Pull out, combined cone failure
		30.4		Pull out, combined cone failure
		29.8		Pull out, combined cone failure
	20 Ø	32.5	33.5	Pull out of the anchor
		33.1		Pull out of the anchor
		35		Pull out of the anchor
UHPSCC samples	10 Ø	21.1	21.9	Splitting in the concrete specimen
		22.8		Pull out of the anchor
	15 Ø	31.8	32.7	Pull out of the anchor
		33		Pull out of the anchor
		33.2		Pull out of the anchor
	20 Ø	32.4	32.4	Yielding of the anchor followed by anchor rupture
		25.5		Steel yielding of the anchor followed by elongation of the bar.
		32.4		Yielding of the anchor followed by anchor rupture
Mortar samples	10 Ø	18	17.1	Pull-out of the Anchor
		16.1		Pull-out of the Anchor
	15 Ø	19.2	20.3	Pull-out of the Anchor
		20.3		Pull-out of the Anchor
		21.5		Pull-out of the Anchor
	20 Ø	26.7	29.6	Pull-out of the Anchor
		29.5		Pull-out of the Anchor

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3.3.1. Failure mode under pull-out load of Ø8 mm bars

The mode of failure of using 8 mm bars in post-installed rebar samples using mortar bonded with embedment lengths of 10Ø, 15Ø and 20Ø is by rebar slippage or pulling-out of the anchor. The similar failure mode was observed in the control specimen (cast in-place), UHPSCC, EPICHOR 1786 when the embedded lengths were less than 15Ø, or at 15Ø and 20Ø, respectively. However, in Sikadure-31CF, the pull-out failure was accompanied with conical concrete failure at the surface boundary of concrete when the embedded length is greater 15Ø. This means that that there is difference in the bond or frictional resistance between adhesive/-concrete interface and adhesive/rebar interface. As the embedded length reduces, the bond strength between adhesive/rebar interface is lower in comparison with the adhesive/concrete. Hence, the crack initiates first in the latter. This could explain the splitting failure recorded when the embedded length is 10Ø in *Sikadure-31CF* (Fig. 5b). Though, further investigation may be necessary on the effect of interfacial difference in the failure mode of adhesive bonded rebar concrete specimens to finally bring this assertion into logical conclusion.

The bond strength between rebar-adhesive interface increases as the embedded length increases. Therefore, rebar will yield if the bond strength develops exceed the characteristic strength of rebar. This effect is displayed by the failure mode of UHPSCC and the control specimen (cast in-place rebar) when the embedded length is Ø20 as shown in Table 8 and Fig. 5c. The yielding failure mode of Ø8 bars occurred in post-installed rebar samples using adhesives when installing the bars with embedment length of 20 Ø (16 cm) suggests insufficient L_d as required by ACI code.

4. Conclusions

Based on the experimental program carried out, the following conclusions can be drawn:

1. The pull-out strengths of the two chemical adhesives – *EPICHOR 1768* and *Sikadure – 31CF* – used in this research were close although the results of *EPICHOR 1768* adhesive gave relatively higher pull-out strength in several samples while it also gave a close average pull-out load value to the cast in place samples using ultrahigh performance concrete (UHPSCC).
2. The pull-out load increases with the embedded length and the diameter of the rebar. This implies that the higher the contact surface of the rebar with the binder or adhesive, the higher the bond strength or the recordable pull-out load.
3. The use of the adhesives and UHPSCC outperformed mortar. However, cost effectiveness and environmental considerations may be the guiding criteria on the choice of adhesives or UHPSCC as a binding agent for post installed rebar concrete applications.
4. Failure mode of post installed rebar concrete is governed by the rebar area of contact with the adhesives or binder and embedded lengths. Larger diameter of rebar favours splitting or failure of concrete due to higher strength in binder-rebar interface compare to binder-concrete interface. The 12-mm diameter rebar was found to be dominated by splitting while 8 mm rebar specimen were characterized by the combination of splitting, yielding of rebar, and slippage while the concrete conical shape failure depending on the type of binding agents and the embedded length.

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