Assessment of available polymer adhesives for bonding new reinforcement with hardened concrete

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A comprehensive study was undertaken to assess different steel-to-concrete polymer adhesives that are commercially available for concrete repair. Bond strengths between inserted bars and concrete using eleven adhesives, including eight epoxy and three polyester-resins, were examined. Cement mortar was incorporated for comparative purpose. Non-traditional test set-up was used where two bars were inserted oppositely in concrete cube and fixed using adhesive. Pullout loads were applied through the bars. A total of 128 specimens were prepared. Variables considered were type of adhesive, loading regime, bar texture, and testing age. Monotonic and cyclic loadings were applied. Bond strength versus bar slippage for each adhesive was demonstrated. Column prototype was implemented and tested using special pullout equipment to simulate field application. Three modes of failure were observed; concrete tension failure, splitting failure, and bond failure indicating poor behavior of the interface. Results show that subject polyesters and some epoxies are not promising. Some adhesives are comparable to cement mortar and sometimes less efficient. Under monotonic loading, perfect bond was observed for four out of eleven adhesives; of which one adhesive showed bond failure due to cyclic loading. Compressive strength of adhesive material does not give any indication regarding its bonding capability. The costs of the two adhesives that showed perfect bond performance are reasonably fair while other much more costly adhesives were less efficient for bonding steel to concrete. Deformed inserted bars may provide only 10% bond enhancement over smooth bars. Traditional pull-out test may overestimate bond strength by 35%. Number of cycles resisted by different adhesives is quit different and failure mode may be changed under cyclic loading. Results obtained from testing prototype support most above findings. In the light of experimental evidences, an acceptance-performance criterion for reliable assessment of polymer adhesives for bonding new reinforcement to existing concrete is proposed.

يقدم هذا البحث نتائج دراسة معملية لتقدير كفاءة اللواصق البولمرية المتوافرة محليا لزرع حديد التسليح في الخرسانة. وقد تم دراسة اجهادات الترابط بين أسياخ التسليح بعد تثبيتها مع الخرسانة باستخدام احدي عشر لاصق بولمري منها ثمانية مواد ايبوكسية وثلاث مواد بوليسترية وكذلك مونة أسمنتية للمقارنة. وتم استخدام اختبار نزع غير تقليدي تضمن زرع سيخين تسليح داخل مكعب خرسانى من الناحيتين وشد السيخين لاجراء النزع، وتم اعداد ١٢٨ عينة لهذا الغرض. وقد اشتملت المتغيرات علي تأثير نوع اللاصق البولمري، ونوع الأحمال المؤثرة (استاتيكية ومتكررة)، وطبيعة سطح السيخ، وعمر الاختبار. وتم عمل نموذج لعمود خرساني لتمثيل التطبيق في الطبيعة. قد لوحظ حدوث ثلاث أشكال للانهيارات تمثلت في انهيار الخرسانة، أو انفلاق الخرسانة، أو انهيار الترابط لضعف اللاصق البولمري. وقد أعطت بعض اللواصق نتائج ترابط مماثلة للمونة الأسمنتية وظهر عدم كفاءة اللواصق البوليسترية. وتبين كفاءة أربع لواصق ايبوكسية فقط ظهر ضعف نوع منها تحت تأثير الأحمال المتكررة. وتبين أن مقاومة الانضغاط للواصق البولمرية لا علاقة لها بكفائتها كمادة رابطة للأسياخ في الخرسانة. واتضح أن تكلفة أقوي لاصقين مقبولة في حين أن لواصق أخري أكثر تكلفة ظهرت بصورة أقل كفاءة في زرع أسياخ التسليح بالخرسانة. وأعطت الأسياخ ذات النتوءات ١٠% زيادة في الترابط عن الأسياخ الملساء. وتبين أن اختبار النزع التقليدي قد يعطي نتائج اجهادات ترابط أعلي من الحقيقة بنسبة ٣٥%. كما تباينت قدرة اللواصق البولمرية في تحمل دورات تحميل متكررة والتي أدت الي تغيير طبيعة الانهيار. وأكدت نتائج اختبارات النزع علي النموذج الخرساني النتائج السابقة. وتوصلت الدراسة الي أسلوب عملي لتقييم كفاءة اللاصق البولمري في زرع أسياخ تسليح جديدة في الخرسانة والذي يلزم نجاحه قبل قبول نوعية اللاصق.

Keywords: Concrete repair, Bond, New reinforcement, Polymer adhesives, Cyclic, Prototype

1. Introduction

The area of repair and rehabilitation of concrete structures is widely increasing and is highly considered one of the main costly issues in concrete industry. Nowadays, it is actually remarkable that many buildings needs repair during their construction.

Actually, Proper remedial work is required to restore the design capacities. Besides, strengthening of concrete elements is sometimes essential for safety. Therefore, bonding new reinforcing steel with existing concrete becomes of fundamental importance to many aspects of reinforced concrete behavior. Additional reinforcement and shear connectors are relied on to ensure that the new section is intact. Therefore, perfect bond becomes a vital issue to ensure the integrity of the composite [1]. Many current detailing provisions are aimed at preventing bond failures. A minimum development length for reinforcing steel in concrete section is hence proposed in most codes [2, 3] to ensure complete force transfer across the interface between concrete and steel. However, the situation becomes trickier for repair projects as compared to new constructions [4]. The success of the entire system depends on the perfect interaction between the new bar and old concrete. In fact, inserted length in the order of 30 cm at the most can be attained by traditional drilling facilities. Consequently, very reliable bonding adhesive rather than traditional cement mortar is ultimately a must.

1.1. Bond behavior - background

Bond was previously recognized by many researchers as the equivalent unit shear stress that acts parallel to the reinforcing steel bar on the steel-concrete interface [5]. It is mainly developed through adhesion and friction for smooth bars, while it relies primarily on the ribs support for deformed bars. In fact, the adhesion is the first acting mechanism but once the adhesion fails, the role of friction and ribs become significant. The influences of several parameters on steel-concrete bond have been previously explored by numerous researchers through both experimental and theoretical studies. These parameters included as variables as bar diameter, bar texture (ribbed or smoothed), concrete strength, concrete cover, casting direction, type of loading and also presence of epoxy coating.

According to Fabbrocino et al. [6], the concrete cover and the casting direction play a major role on bond strength of smooth bars. Xio and Falkner [7] also reported that bond strength for smooth bar is affected by concrete ingredients much more than deformed bars. Chapman and Shah [8] examined the bond strength between steel and concrete at early age. Variables studied were bar texture, embedment length, and concrete ages. They have concluded that the effect of concrete age on bond strength is more pronounced for deformed bars as compared to smooth bars, and also that the development length required by ACI Code (ACI 318M) [3] is underestimated at early ages. Most researchers agreed that higher concrete compressive strength develops higher bond strength [9]. However, Treece and Jirsa [10] have concluded that bond strength of epoxy-coated bars was independent of bar size and concrete strength.

On the other hand, the effect of loading frequency on bond strength have been investigated by Balazs [11] based on the results of more than 100 cyclic pull-out tests including various load histories. It was concluded that repeated loading produces a progressive deterioration of bond caused by the propagation of micro-cracks and progress of micro-crushing in concrete. This agrees with Jose et al. [12] who examined the static and dynamic bond behavior of metallic and non-metallic bars embedded in a polyester polymer concrete. They found that fiber reinforcing polymers rods did not show fatigue under their load level as steel rods behaved. In a recent paper published by Kim et al. [13], the effect of loading rate on pullout behavior of deformed steel fibers were investigated. It was concluded that twisted steel fibers shows rate sensitivity that is dependent on the compressive strength of the matrix. A comprehensive report regarding bond under cyclic loading have been also reported By the ACI Committee 408.2R, 2008 [14].

Abrishami and Mitchell [5] have published a very interesting technique to simulate uniform bond strength and force transfer across the interface between concrete and reinforcing steel bars. Also, based on limited number of specimens, Rizkalla et al. [15] proposed a modification to the equation given in ACI 318 to predict the bond forces beyond the proportional limit for three special types of high-strength steel reinforcement. Other researchers examined bond strength under different circumstances. Auyeng et al. [16] studied the bond behavior of corroded bars and concluded that bond is not completely destroyed due to extensive corrosion with considerable concrete cracking.

In the light of literature evidence, it appears that most researchers studied bond in new concrete while technical literature of performance of new inserted bars in concrete is non-comprehensive. Actually, the introductory of any adhesive material make the situation more complicated by involving two interfaces and certainly the adhesive material itself plays a major role.

The effect of surface moisture (wet or dry) on the micro tensile bond strength of many bonding adhesives was studied by Manso et al. [17]. They concluded that the surface moisture affected the bond strength in different ways for different adhesives. Also, the effect of loading rate on the ultimate pullout resistance of chemically bonded anchors subjected to rapid tensile load was investigated by Fujikake et al. [18]. They reported that the dynamic ultimate pullout resistance increases with an increase of the loading rate. Based on the performance of reinforced concrete beams strengthened by externally bonded steel plates, Barnes and Mays [19] investigated the transfer of stress through steel to concrete adhesive and proposed a two-dimensional non-linear finite element model for this application.

From another prospective and according to ACI 503.5R-92 [1], wide range of polymers adhesives that are different in cost and performance are available for concrete repair. This includes both epoxy resins and polyester resins. Whereas epoxy-resin adhesives have been recognized as a highly effective bonding material polyester-resins have found only limited use as adhesives [1, 20] because of their relatively high shrinkage while curing.

1.2. Available testing approaches – state-of-the-art

Different standards and researchers used several tests that are not similar in principle, to study bond strength between steel and concrete as shown in fig. 1. The American Society of Testing and Materials (ASTM) introduced in previous editions the concentric pullout test (ASTM C 234) that is outlined in fig. 1-b. Unintentionally, many researchers followed this setup for general assessment of steel-concrete bond although the intent of ASTM was to use the test as a comparative tool between different concretes [4]. In fact, this setup leads concrete to be under compression while in reality the bond concern is in the tension zone where both concrete and steel are under tension. It should be noted that this standard was withdrawn starting from the 2000-version of ASTM. Eccentric pullout test shown in fig. 1-c seems to be more representative for flexural member; however it does not allow the common diagonal tension cracks to occur [8]. Cantilever beam test fig. 1-d, and modified beam test, fig. 1-e, require complicated preparation and can hardly be performed due to lab facility. Double reinforced prism approach followed by Auyeung et al. [16] and Chapman and Shah [8] seems to be simple and represents to a large extent the real case where concrete is under tension as seen in fig. 1-f.

On the basis of the above argument, it was decided in the current study to use the double reinforced prism approach but with different dimensions for concrete block. Loads will be applied to the specimen through the two bars. It is believed that this setup is the most appropriate one for evaluating the bond between concrete and inserted bars.

2. Research significance

Many polymer adhesives are commercially available and are nowadays employed as a main tool in the repair and rehabilitation of concrete projects in order to effectively fix new inserted reinforcing steel into existing hardened concrete. These adhesives includes as many as epoxy- and polyester-based resins that involve two or three components, with or without fillers. Since the performances of such materials are relatively vague for most engineers and contractors, the cost of the adhesive materials and to some extent undependable advises become the main keys for material selection. In fact, a performance-based approach for selecting proper material for bonding new steel to concrete becomes mystery. The situation becomes disastrous due to modifying the materials that are periodically made by manufactures to reduce the cost. The data provided by the supplier are mostly the only key source of information. However, the technical data sheet of each material implies that the subject material is tremendous and can assure perfect bond between the rebar and surrounding concrete in addition to other perfect properties. But, actually is that true? Can we really depend on the information given by the provider? The safety of human beings deserves much more consideration. From that point, this study is undertaken.

3. Experimental program

3.1. Scope

The program involved laboratory and prototype testing. The bond strength was studied using non-traditional pullout test similar to that reported elsewhere [8, 16], while special pullout equipment was used for testing prototype to simulate real field. The lab program consisted of a total of 128 pullout specimens; 80 specimens were tested at early age and the remaining specimens were tested after 5 years under monotonic and cyclic loadings. Specimens involved 16 mm-smooth bars and 12 mm-deformed bars. Variable considered were type of adhesive materials, type of loading, and age of testing. Direct comparison between the current test setup and the traditional pullout test according to the former ASTM C234 is addressed. It should be emphasized that this standard has become inactive since 2000. The term 'materials' refers here to the bonding adhesives used throughout the program. Eleven polymer materials were examined including epoxy- and polyester-resins.

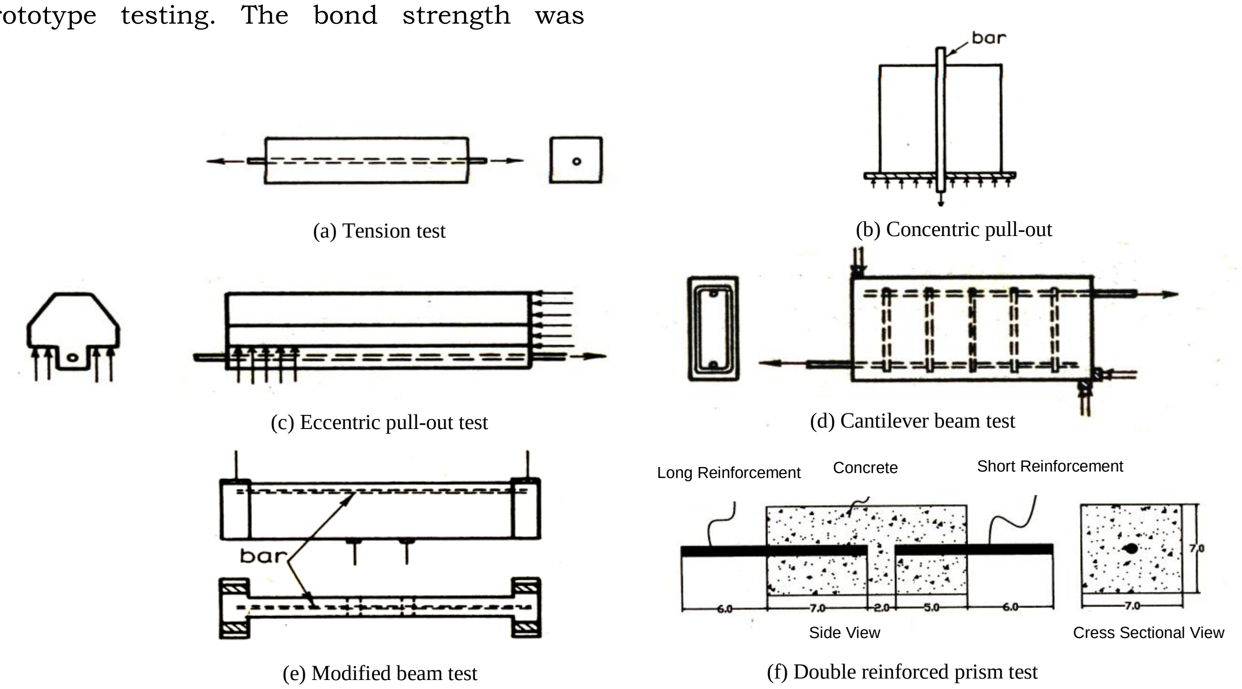


Fig. 1. A variety of test arrangements for evaluating steel-concrete bond.

Table 1
Concrete mix proportions

Target strength, MPa	Concrete ingredients per cubic meter of concrete					
	Cement, liters/m³	Water content, liters/m³		Sand, kg/m³	Crushed stone, kg/m³	Admixture type F, liters/m³
		Total water	Free water			
40	400	160	139	685	1090	7.0

3.2. Materials and mix proportions

Portland cement CEM-I from one local source (Alexandria Cement Company) was used in all mixes. This cement was known by the time of casting as Ordinary Portland cement (ASTM Type I). Siliceous graded sand with fineness modulus equal to 2.64 was used as a fine aggregate, while crushed pink lime stone having nominal maximum size of 19 mm was used as a course aggregate. The unit and specific weights of the used coarse aggregate were 1.48 t/m^3 and 2.51, respectively. High range water reducing admixtures (ASTM Type F) was incorporated in the mix to ensure workability. One concrete mix of grade 40 MPa was used. The mix proportions are given in Table 1. The steel bars were 16 mm smooth bars of grade 24/36 and 12 mm-deformed bars of grade 40/60. Mechanical properties of the steel are given in table 2. It should be noted that the 16 mm- smooth bars were relatively available by the time of starting the program. Actually, it was decided to use the latter type of steel in many specimens in order to eliminate the effect of ribs support and hence to highlight on the adhesion effectiveness of the bonding materials.

The used bonding materials were produced by ten chemical companies. The materials included eight epoxy-resins and three polyester-resins adhesives. The materials are coded from M1 to M12. Material 'M5' refers to rich cement mortar that contained three parts of cement and one part of graded sand by weight with water-cement ration equal to 0.278.

3.3. Concrete fabrication and curing process

Concrete was mixed in a 0.25 m^3 capacity rotating pan mixer. The aggregates were mixed first then cement was added and mixed thoroughly. The water and chemical admixtures were then added and mixed for three minutes followed by a rest for two minutes then mixing was re-continued for another three minutes. Considering lab facilities, all concrete cubes (about 0.50 m^3) were cast using three batches. Cubes were cast and left for 24 hours at room temperature then concrete cubes were removed from the moulds and cured in lime-water for 14 days then left to dry for another 14 days before starting the test preparation. The concrete strength by that time reaches 34.0 MPa. It should be noted that the casting process was performed in January where the typical day temperature was 15^{o}C.

3.4. Inserting process

Two holes were drilled inside each concrete cube at the centers of two parallel sides other than the top unsmoothed surface. In another words, the steel bars were inserted in a direction perpendicular to the direction of casting. The diameters of holes were kept constant at 4 mm in excess to bar diameter. The embedment length was kept comparable at 75 mm at each side of all cubes. One hole was drilled firstly and filled with the pre-prepared adhesive, and then a bar was inserted vertically in that hole till the end and rotated half a circle to ensure full contact. It was attempted to keep the vertical alignment of the bar until material setting. After 24 hrs, the subject cube was flipped and similar work was done to insert the other bar in the other side using the same material. It was ensured that holes were dry and free from any dirty substance before pouring the material.

Table 2
Mechanical properties of used steel

List No.	Nominal diameter, mm	Steel grade	Effective diameter, mm	Yield load, kN	Yield stress, MPa	Ultimate load, kN	Ultimate stress, MPa	%age of elongation
1	12	40/60	11.80	47.0	429.8	75.00	685.8	18.30%
2	16	24/36	16.23	57.49	277.9	85.78	414.6	27.50%

Different adhesives were prepared as described in their relevant data sheet. Mechanical mixing was adopted for mixing the components of specific material until fully blended with uniform color. This process was executed by expert technicians from the materials' suppliers. Generally, each material was prepared twice in two consecutive days. Wherever cement mortar was used for bonding the steel bars concrete cubes were left in water for 24 hours before application. Many specimens were discarded due to the improper drilling or alignment or even material setting before application. Eight to fifteen cubes were prepared using each material. Fig. 2 shows some cubes tested at early ages. Mostly, three to five specimens using one adhesive material represented a set of test specimens; however some sets tested at five years involved two cubes. Preparation of specimens were completed within three months of bushed work.

3.5. Testing

Tests were performed using 300 kN universal testing machine at the material laboratory in the Faculty of Engineering, Alexandria University. A displacement control mode with a typical rate of 2 mm/min was followed in all monotonic loading. The first group of specimens (80 cubes) was tested at early ages starting at 3 days after the inserting process and the pullout loads were recorded. At later ages (5 years) the bar slips were monitored during testing using two dial gages with sensitivity 0.01 mm that were attached to the two steel bars as shown in fig. 3. The readings of the dial gages were recorded up to failure. Bar slip was considered as the largest reading of both dials. Readings were corrected for the elongation of the reinforcing bar in the distance between the surface of concrete cube and the point on the steel bar where the dial gage was attached. The elastic modulus of steel was assumed herein to be 200 GPa. The yield points of the reinforcing bars were not reached throughout the program. Actually, the pulled-out bars were stressed up to 0.25 to 0.50 of their yield stresses.

4. Test results and discussions

4.1. Monotonic loading:

The bond strength in all cases is assumed to be uniform around the embedment bar and hence is calculated using the following well-known formula:

$$f_b = P_u / \pi D L, \qquad (1)$$

Fig. 2. Specimens tested at early ages.

Fig. 3. Dial gages attached to the specimens.

where P_u is the ultimate recorded load, D is the bar effective diameter, and L is the embedment length that was kept constant at 75 mm in all specimen. At early ages, smooth and deformed bars were incorporated.

Mainly, three modes of failure were observed during testing:

I. *Bond failure:* where one embedded bar was completely pulled out of concrete cube while the concrete was still intact. This mode indicates poor steel-concrete interface and inadequacy of the adhesive.

II. *Splitting failure:* where concrete cube was split vertically parallel to loading direction due to shear and the bars were pulled out with or without concrete piece indicating, respectively, fair to poor bond.

III. *Concrete failure:* where the concrete cube split into two halves perpendicular to loading direction while both embedded bars remains perfectly bonded with concrete indicating perfect bond.

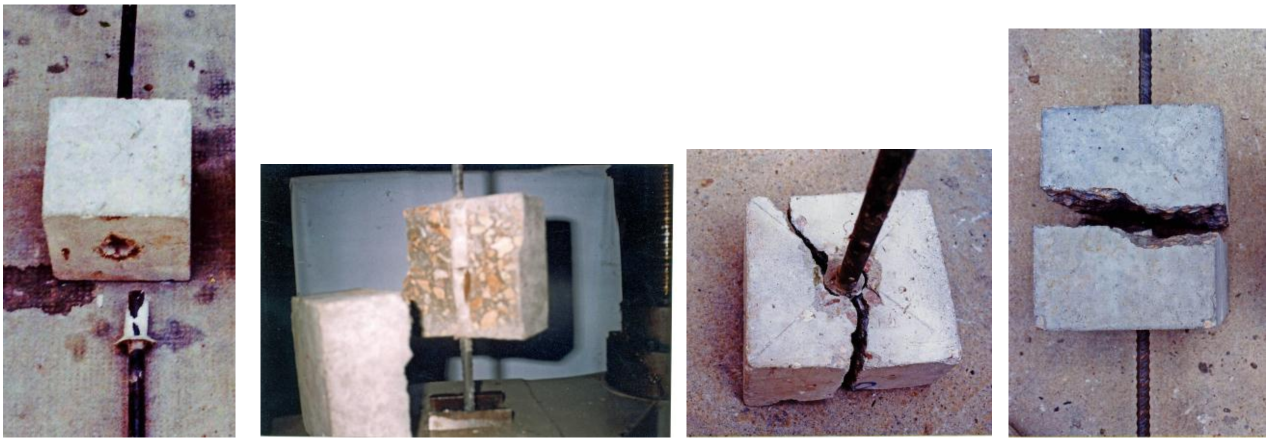
In some materials, the mode of failure changed from concrete failure at early age to bond failure at later ages due to the improvement in concrete strength. It should be noted that wherever concrete failure occurred, the bond strength is actually in excess of calculated values. Different failure modes are given in figs. 4 to 6. Similar modes were reported elsewhere [12].

Two parameters are introduced herein to provide a reasonable basis for consistent assessment of the bond performance at late ages. These parameters are defined as follows:

1. *Bond Index K:* which is defined as the slope of the line passing from the origin and the ultimate bond strength, i. e. $K = f_b/\Delta_u$, where Δ_u is the bar slips corresponding to the bond strength f_b.
2. *Effective strength f_e:* which is defined as the calculated bond strength at the point where the bar slip reaches 0.4 mm.

Results at early and later ages are listed in table 3. The number of tested specimens and the observed modes of failure are also presented.

It should be pointed out again that in all tested specimens the maximum developed normal stresses in all steel bars due to applied tension was less than the yielding point. The bars remained within the elastic domain far away from the plastic plateau. Therefore, sudden increase in the dials' readings was attributed to bond failure at the interface not due to steel yielding.



(i) Bond failure (ii) Splitting failure (iii) Concrete failure

Fig. 4. Modes of failure.

Table 3
Results of 110 pullout tests under monotonic loading

Bonding Material	Monotonic Loadings													
	Testing at early ages (concrete age > 28 days)								Testing after 5 years					
	12 mm-deformed bars				16 mm-smooth bars				16 mm-smooth bars					
	No. of tests	Ava. Pullout load P kN	Ava. bond strength MPa	Mode of failure	No. of tests	Ava. Pullout load P kN	Ava. bond strength MPa	Mode of failure	No. of tests	Ava. Pullout load P kN	Ava. bond strength MPa	Mode of failure	Effective strength f_e, MPa	Bond index K
M1	4	18.96	6.82	S+B	4	20.65	5.40	S+B	3	25.81	6.75	C+S	6.75	193
M2	3	21.85	7.86	C	3	24.86	6.50	S+C	2	29.33	7.67	C	7.67	284
M3	4	32.00	11.51	C	4	35.83	9.37	C	3	30.59	8.00	C	8.00	242
M4	4	13.71	4.93	B	4	13.96	3.65	B	2	14.42	3.77	B	2.72	54
M5	4	17.43	6.27	B	4	20.08	5.25	B	2	23.06	6.03	B	2.90	12
M6	4	28.28	10.17	C	4	35.14	9.19	C	3	29.45	7.70	C	7.70	285
M7	4	30.86	11.10	C	5	35.18	9.20	C	3	31.89	8.34	C	8.34	261
M8	5	25.41	9.14	C	3	23.78	6.22	B	2	24.55	6.42	B	6.05	107
M9	3	22.10	7.95	S+B	3	20.38	5.33	B	2	25.77	6.74	B	4.39	81
M10	3	34.40	12.38	C	3	36.94	9.66	C	3	34.03	8.90	C	#	#
M11	3	33.53	12.06	C	3	35.95	9.40	C	2	31.36	8.20	C	#	#
M12	3	27.33	9.83	C+S	3	30.59	8.00	C+S	2	30.21	7.90	S	#	#

B: bond failure (Mode i)
S: splitting failure (Mode ii)
C: concrete failure (Mode iii)
#: The ultimate reading only was recorded.

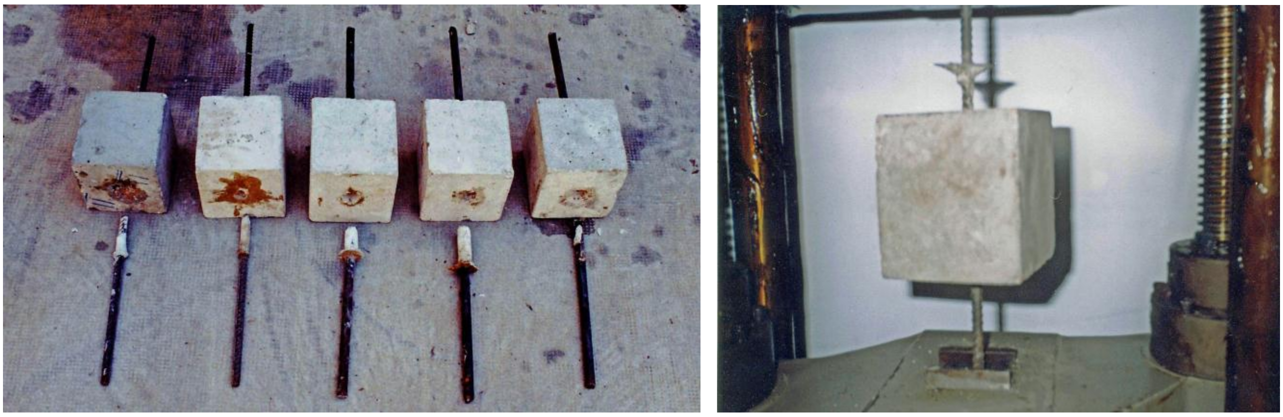


Fig. 5. Bars completely slipped out of concrete indicating bond failure at early ages.

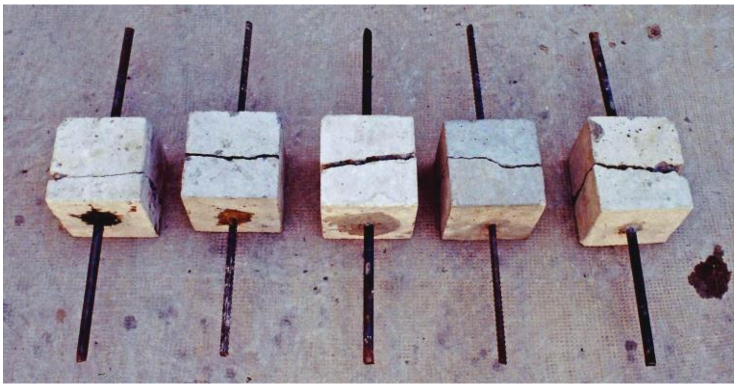


Fig. 6. Perfect bond for Materials M3, M6, M7, M10, M11 at early ages.

4.1.1. Effect of bonding material

Testing at early ages: The performances of all materials were somewhat different. Data listed in table 4 clearly indicates that the best performance was noticeable for the epoxy adhesives namely M3, M6, M7, M10, M11 that exhibited bond strength varying from 9.19 to 9.66 MPa for smooth bars and from 10.17 to 12.38 MPa for deformed bars. The mode of failure using these materials was governed by concrete failure while the bars were still perfectly bonded with concrete. Contradictorily, the poorest behavior among the twelve studied materials, including cement mortar, is shown by Material M4 which could undergo only 3.65 MPa of bond strength for smooth bars and 4.93 to MPa for deformed bars. Actually, the bond strength attained using Material M4 is about from 40% of that achieved by Material M10.

Table 4
Comparison between different types of materials

Material	Early age testing											
	Excellent epoxies					Polyesters			Fair to poor epoxies			Mortar
	M10	M11	M3	M7	M6	M8	M9	M12	M1	M2	M4	M5
Φ	12.38	12.06	11.51	11.10	10.17	9.14	7.95	9.83	6.82	7.86	4.93	6.27
12mm	Average = 11.44 MPa					Average = 8.97 MPa			Average = 6.54 MPa			MPa
ϕ	9.66	9.40	9.37	9.20	9.19	6.22	5.33	8.00	5.40	6.50	3.65	5.25
16mm	Average = 9.36 MPa					Average = 6.52 MPa			Average = 5.18 MPa			MPa

Results of smooth bars imply that the bonding efficiency of the costly adhesives M1, M4, M8, M9 are very comparable with that of cement mortar. Their bond strengths varied from 0.70 to 1.18 of that for mortar. Results also indicated that for smooth bars, the bond strength attained by polyester-resins varies from 5.33 MPa to 8.0 MPa indicating poor to fair performance. It is of interest to note that polyester-resins are usually slightly cheaper than epoxies but in local market some polyester-resins are more costly than good epoxy-resins. Above argument leads the one to conclude that arbitrary selection of adhesives for repair projects may lead to improper work and sometimes to unsafe structure.

At this stage, the construction of fig. 7 raises a critical issue. The figure correlates both price and compressive strength of each material (on the right y axis) to the bond strength using smooth and deformed bars (on the left y axis). The compressive strengths of the studied adhesive materials, based on 50 mm cubes, vary from 45.1 to 106 MPa, and their commercial prices vary from 12.0 to 87.0 Egyptian pounds/kg (LE/kg) besides the price of Material M2 that is sold differently and after conversion to kg-unit its price becomes about 180 LE/kg.

As evident from the graph, the compressive strength of the materials M4, M2, and M7 are comparable while the bond strength attained by using these three materials are completely different giving 3.65, 6.50, and 9.20 MPa for smooth bars, and 4.93, 7.86, 11.1 MPa for deformed bars. Also, the compressive strength of Material M10 is about 0.65 of that for Material M8 while the latter provided bond strength about 1.5 times of the bond strength achieved by Material M10. Besides, the compressive strength of the three studied polyester-resins (M8, M9, and M12) are higher than all other epoxy-resins but also show mush less bond performance when compared to other five epoxies. It can therefore be concluded that compressive strength of adhesive material itself does no reflect its adhesion capability.

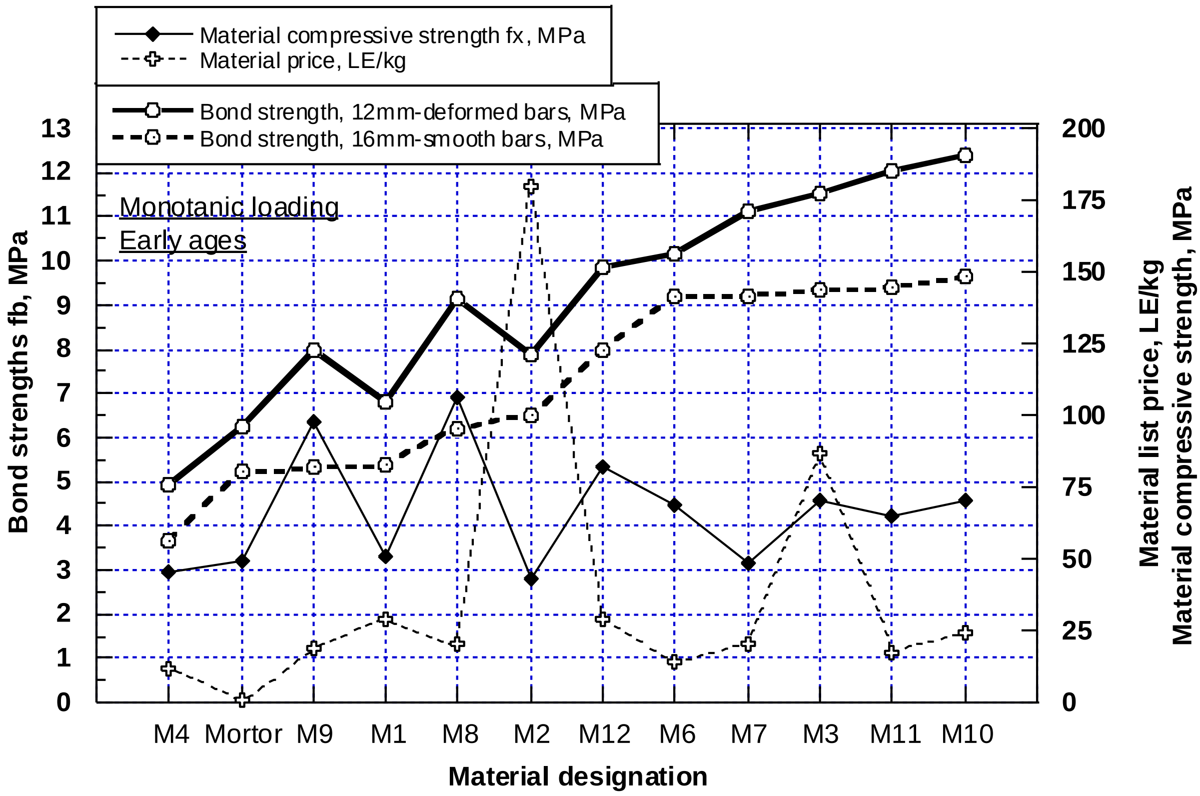


Fig. 7. Bond strength as affected by the material compressive strength and its price.

Unexpectedly, the figure demonstrates that the most expensive material M2 (160 LE/kg) gives fair performance while the best performance was attained by the two materials M11 and M10 that have reasonable prices (24 and 17 LE/kg). From another point of view, the bond strength achieved by the polyester material M12 and the epoxy material M6 are very comparable while the price of M12 is twice as much as the price of M6 (29 vs. 14 LE/kg). It is strongly believed that the price of any adhesive material may play a misleading rule in selection of proper steel-concrete bonding material.

Testing at late ages (*5 years*)

The analyzed results are represented graphically primarily in the form of bond stress-bar slip relationships for the materials from M1 to M9. Each graph also includes the photograph of the relevant specimen at failure as shown in fig. 8 to 16. It should be noted that the complete curves could not be detect for the three materials M10, M11, M12 but the ultimate pullout loads were recorded. All curves are plotted together for direct comparison in fig. 17 while the values of bond index K are compared in table 3. In addition, the effective bond strength (f_e), corresponding to bar slip 0.4 mm, is used as a tool to compare between the different materials as shown in fig. 18 where the materials are arranged in ascending order based on achieved bond strength. It should be mentioned that the concrete strength by that age (5 years) reached 40 MPa. It should be also noted that the approach of considering the bond stress corresponding to limited bar slip was previously adopted in a recent paper published by Xue et al. [9] where the authors examined the bond properties of carbon fiber-reinforced polymer strands in different bonding agents including epoxy-resins. They have concluded that the bond stresses reach a maximum when slippages of strands range from 0.3 to 0.4 mm.

A performance-based classification of the subject materials may also be seen in Fig. 18. It is strongly believed that in good bonding the bar movement would not exceed 0.40 mm. Therefore, the effective bond strength (f_e) is considered equal to bond strength in Materials M10, M11, and M12.

Observed modes of failure are almost similar to those described earlier for specimens tested at early ages as seen in Fig. 19. The poor bonding performance of the cement mortar and other three materials (M4, M8, and M9) is evident. Bond failure clearly occurred and the pulled-out bars exhibited considerable bar slip that cannot be neglected. Inadequate bond strengths are noticeable as seen in fig. 17 and 18. Also, the bond indexes (k) are very low for these materials and varied just from 54 to 107 as compared with k = 285 for the materials M2 and M6. It should be noted herein that the materials M8 and M9 are two polyester-resins out of three polyesters used in the study.

Better trend can be observed for the material M1, M2, M6, and M12 where the bond strengths vary from 6.75 to 7.9 MPa for 16-mm smooth bars and the modes of failures fluctuated from concrete failure (Mode iii) to splitting failure (Mode ii). However, these materials are not completely satisfying and may be classified as moderate adhesives that may not be used in significant cases.

Out of the eleven adhesive materials tested throughout this program and are currently widely used in the Egyptian market, only four materials are appreciated. These adhesives are M3, M7, M10, and M11. Actually, the four mentioned materials are epoxy-resins and showed comparable high bond strength for smooth bars at late ages and have very reasonable price except for the costly material M3 as presented in table 5. Results obtained at early ages using these four materials with 12 mm-deformed bars are also included in the table.

Table 5
Grouping of promising adhesives

Materials designations	M3	M7	M10	M11	Average
Bond strength of 16 mm-smooth bars, MPa	8.0	8.34	8.90	8.20	8.4
Bond strength of 12 mm-deformed bars, MPa	11.51	11.10	12.38	9.83	11.2
Price, Egyptian pounds (LE)/kg	87	20	24	17	-

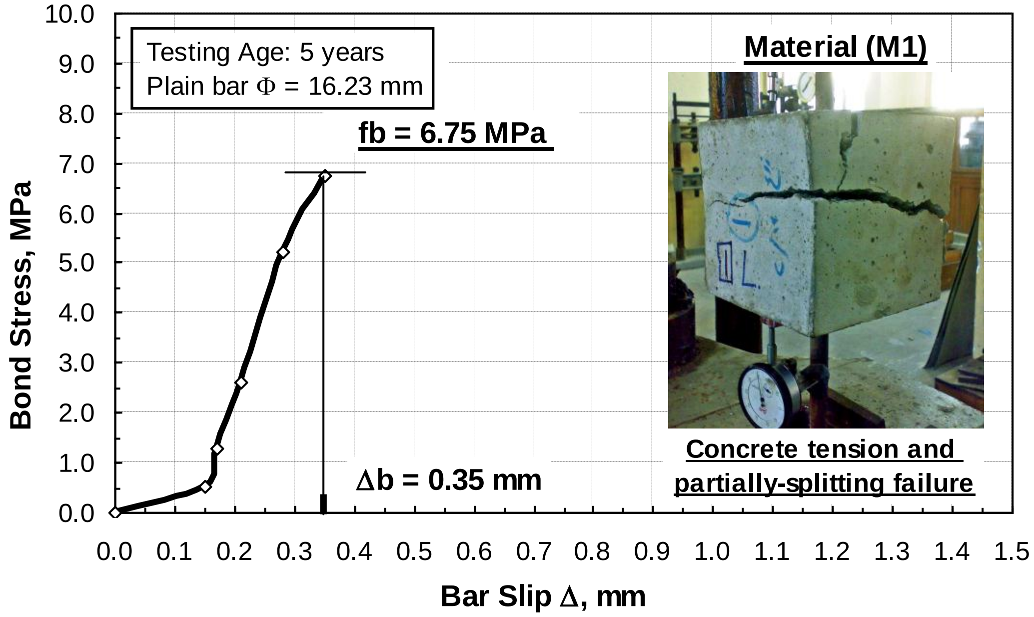


Fig. 8. Bond stress versus bar slip for material "M1".

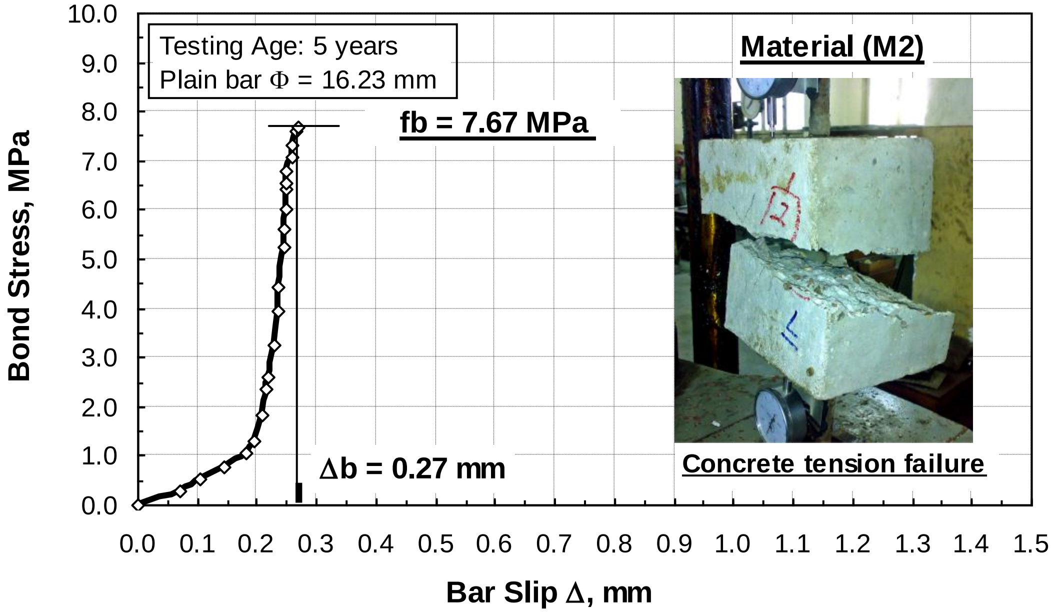


Fig. 9. Bond stress versus bar slip for material "M2".

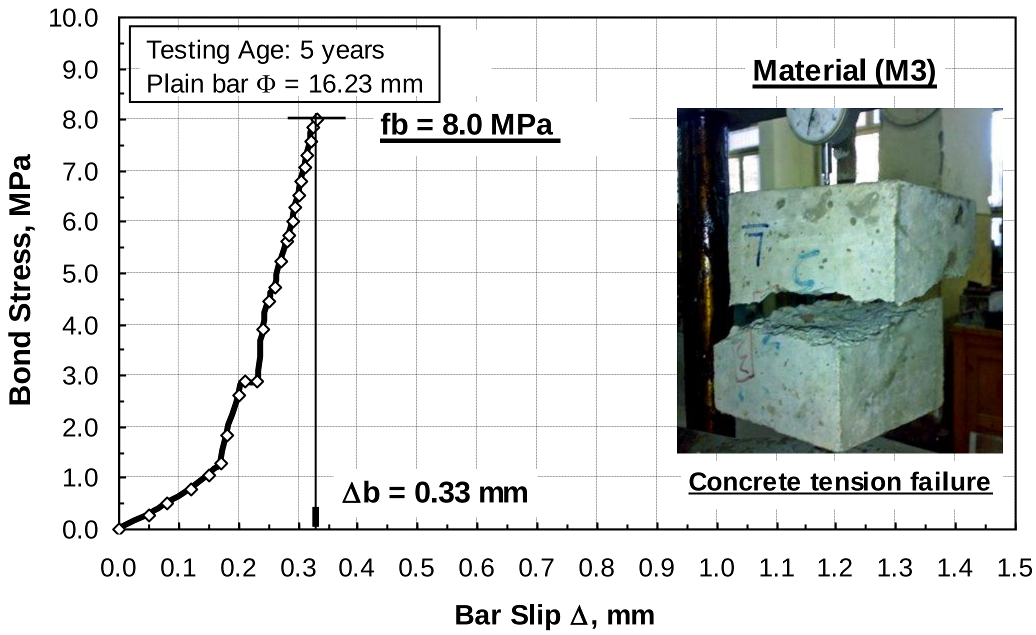


Fig. 10. Bond stress versus bar slip for material "M3".

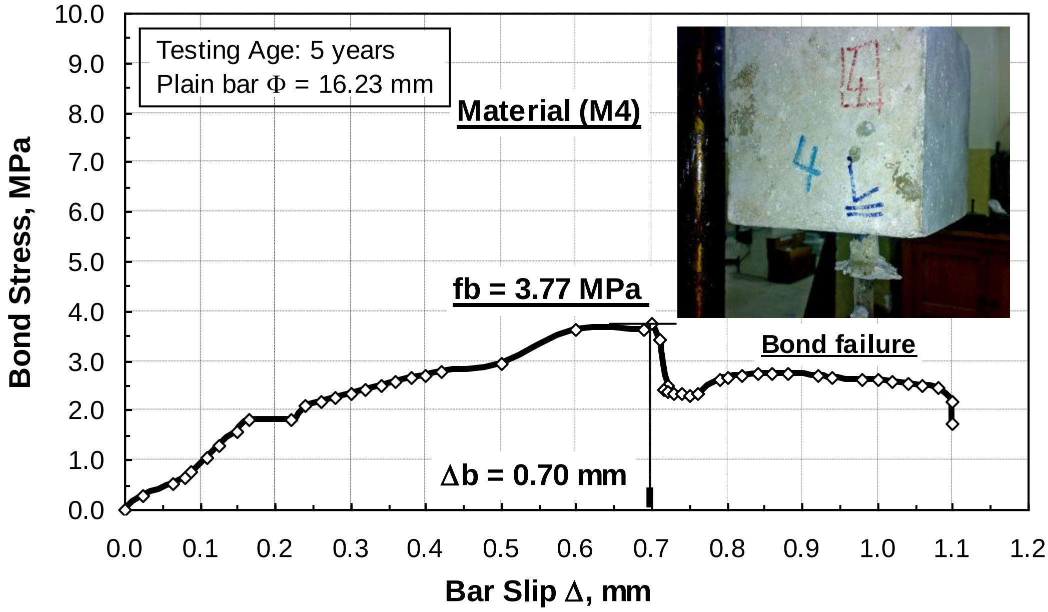


Fig. 11. Bond stress versus bar slip for material "M4".

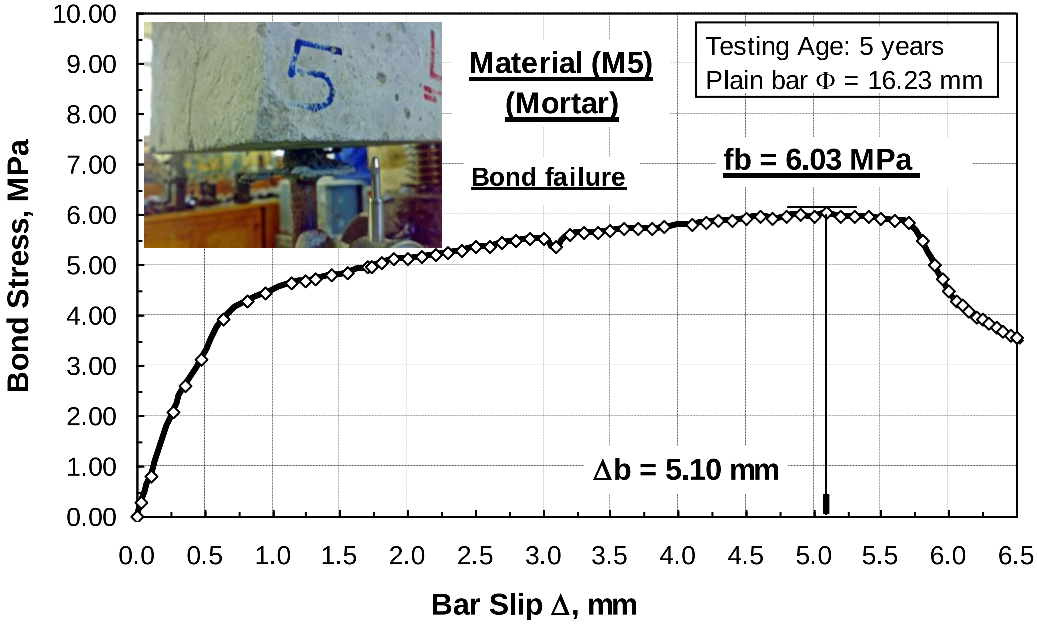


Fig. 12. Bond stress versus bar slip for material "M5".

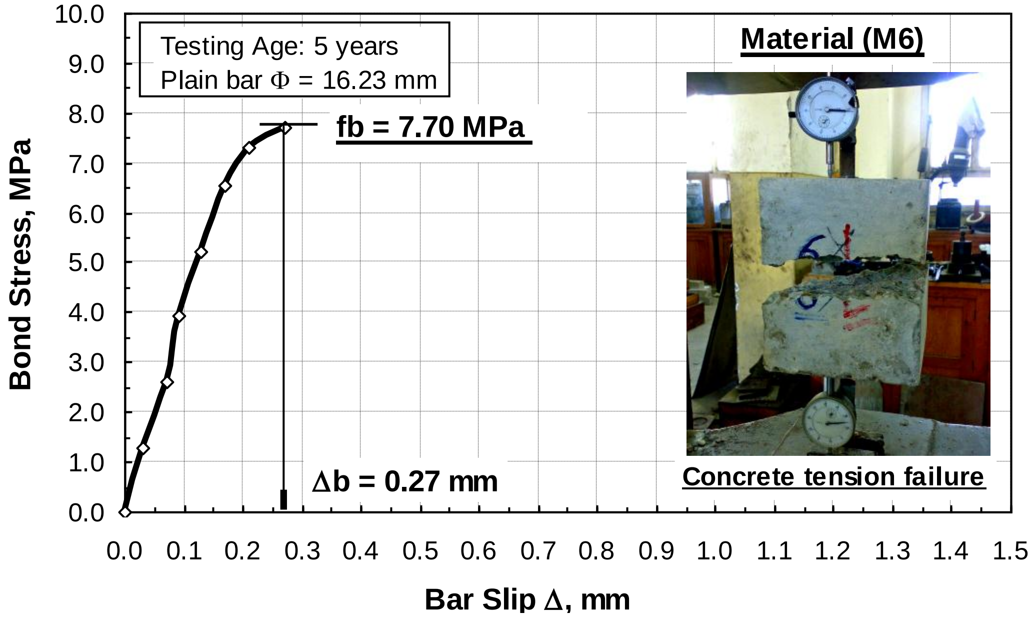


Fig. 13. Bond stress versus bar slip for material "M6".

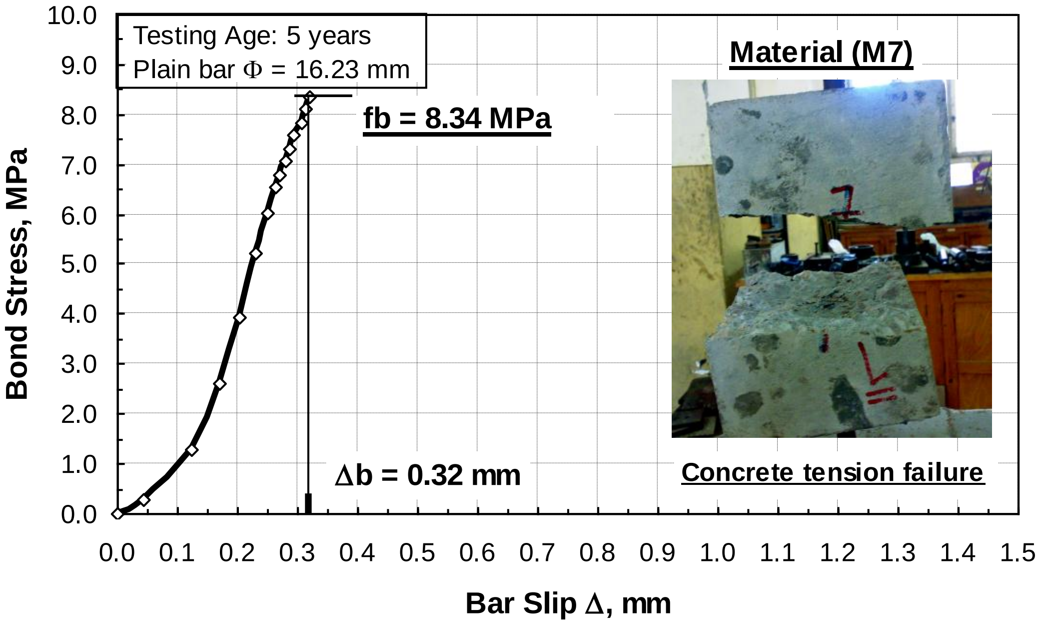


Fig. 14. Bond stress versus bar slip for material "M7".

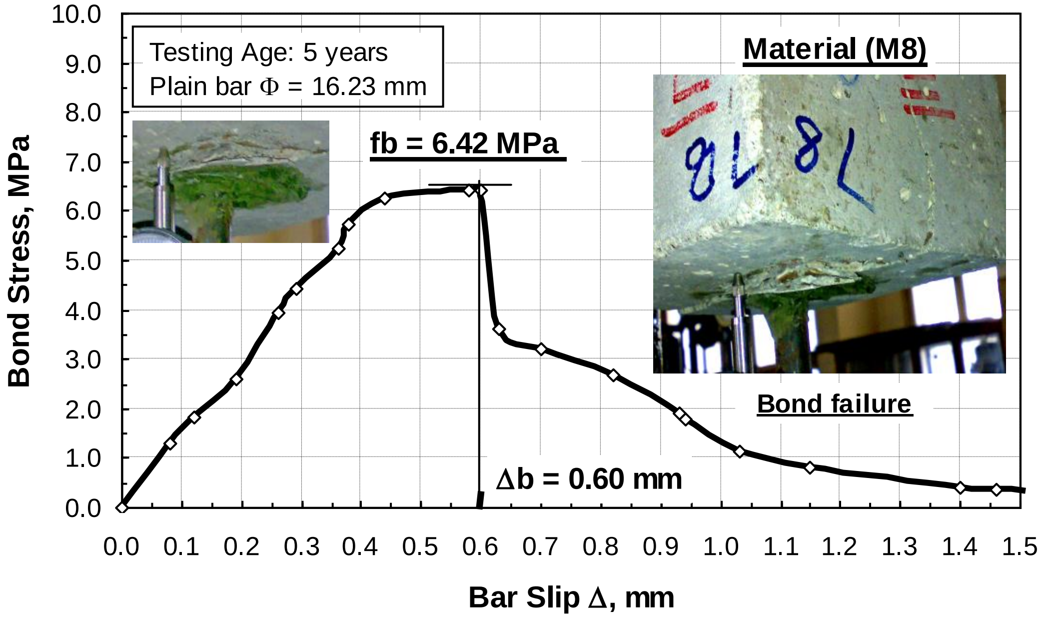


Fig. 15. Bond stress versus bar slip for material "M8".

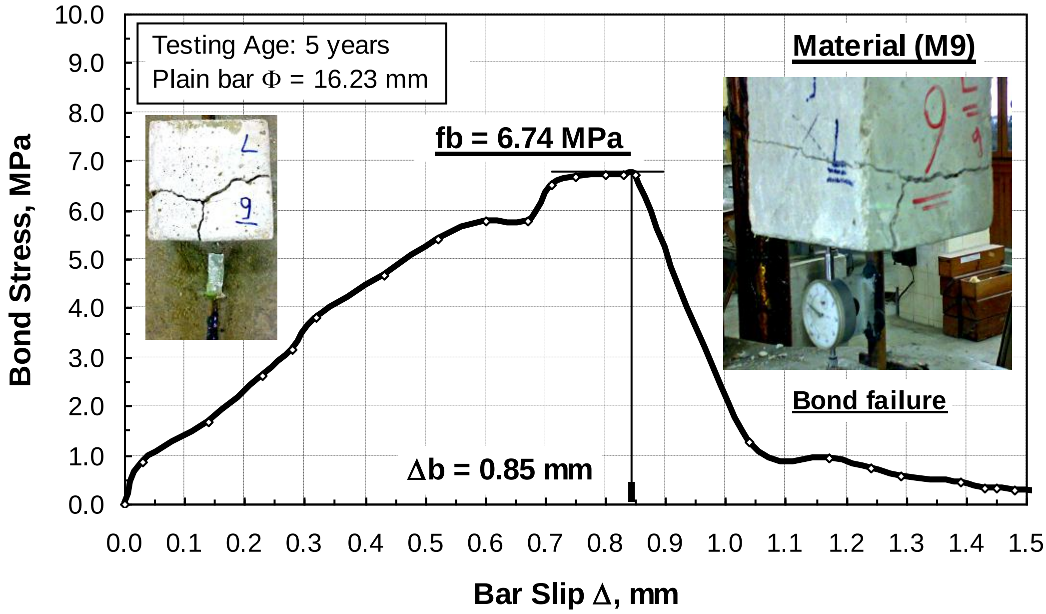


Fig. 16. Bond stress versus bar slip for material "M9".

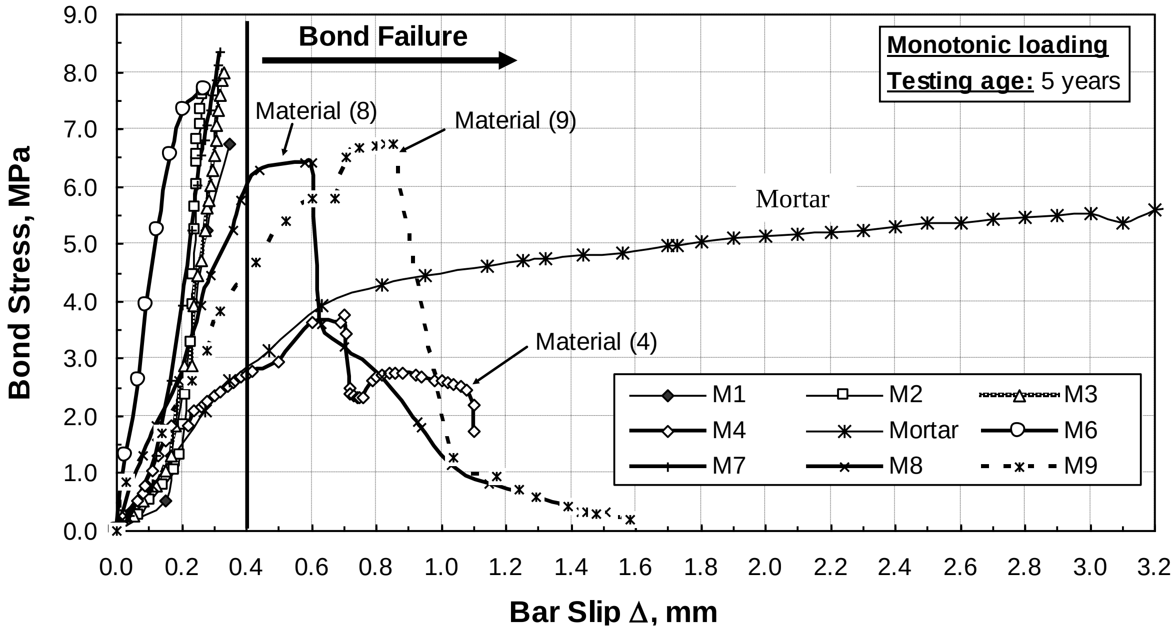


Fig. 17. Comparison between different materials.

It is of interest to note that other researchers recommended the use of cement paste as a bonding material between hardened concrete and newly fresh concrete based on the results of Arizona slant shear test. This finding was previously reported by Elkurdi et al. [21] based on experiments that incorporated seven types of SBR materials (styrene butadiene rubber), four acrylic materials, and nine epoxy-resins. However, the scope of the current work is completely different. In practice, the required development length for steel reinforcement ranged from 40 to 60 times the bar diameter to ensure proper stress transfer. This length can not be attained by drilling process. A length of about 30 cm at the most may be executed in the field by normal drilling facility. For this reason, the bond strength implemented by the Egyptian Code (ECS 203 – Section 5-2-4) [2] and ACI Code (ACI 318M) [3] is not aimed for repair projects. For concrete compressive strength reaching 40 MPa, the bond strength according to ECS 203 is 5.4 MPa. This low strength level can be attained by cement mortar; however it is not safe for repair projects. From general prospective, twice as much as this strength level may be required in repair projects.

4.1.2. Effect of other variables

Most researchers agreed that the bond strength increases for smaller bars and also increases for deformed bars. The Egyptian Code in Section 5-2-4 implies that for comparable concrete, the bond strength of deformed bar is about 33% higher than that for smooth bar. This agrees with Chapman and Shah [8]. Also, Mohamed and Clark [22] reported 100% improvement in bond strength of deformed bar with respect to smooth bars under similar conditions. An improvement by up to 40% was also reported by Kurdi and Khoury [23]. However, those researches considered new concrete work not remedial work.

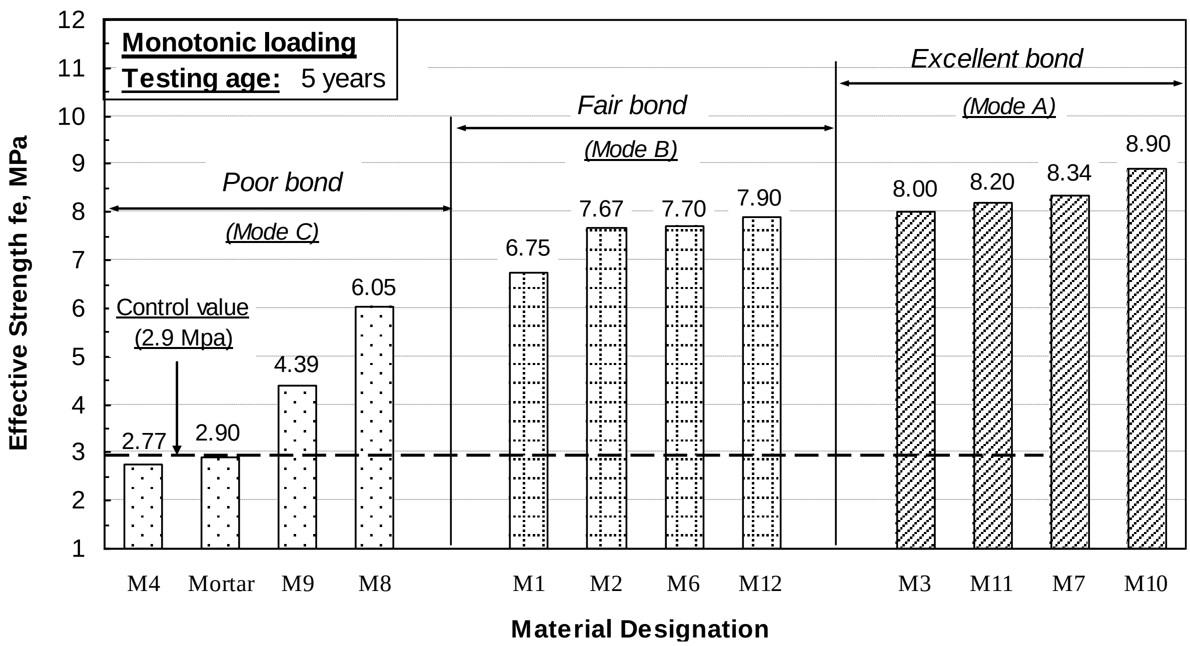


Fig. 18. Classification of materials based on effective bond strengths (f_e).

Fig. 19. The two extremes modes of failure at later ages under monotonic loadings.

In this study, the combined effect of bar diameter and surface texture can be obtained from table 3 where the results of 12 mm-deformed bars are compared with those of 16 mm-smooth bars at early ages. Results of used materials, excluding the polyester-resins M8 and M9, indicate that for a given adhesive the bond between inserted 12 mm- deformed bars and surrounding concrete is higher by about 11% (M6) to 28.7% (M11), with an average value of 22%, than that attained for 16 mm-smooth bars. It seems that most of this improvement is due to the bar diameter while the support of the ribs has a minor rule.

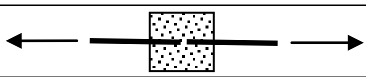
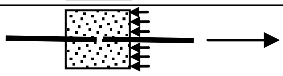
Based on the above argument, it can be concluded that in repair projects the difference between smooth and deformed bars with respect to bond strength is less pronounced than in new construction. It seems reasonable to consider that an improvement in bond strength on the order of 10% at the most may be achieved when using deformed bars rather than smooth bars with comparable effective diameters. This finding supports the importance of proper selection of bonding material in the area of concrete repair and strengthening.

On the other hand, the effect of age on bond strength seems to be not clear. Comparing the results of each group of companion specimens tested at early and late ages indicates some improvements for some materials and reductions for the others. However, these differences that vary from +26% to -16% may be attributed to within-test variations, the accuracy of the testing machine due to the 5 year-period, or may also be due to another reason that is currently unclear. These noticeable reductions in bond strength are associated with perfect adhesives. It should be pointed out that all specimens were placed outdoor during the 5 year-period and were subjected to direct sun and rain! However, this circumstance is outside the scope of this research.

4.1.3. Effect of test setup

The current used setup is compared with the well-known setup that included in the former edition of ASTM (C234) but withdrawn in 2000 and replaced with another approach (A0944). Tested specimens incorporated the least effective adhesive (M4). The embedded length was 75 mm and the effective bar diameter was 16.23 mm (smooth bars). Results (average of two specimens) are included in table 6.

Table 6
Effect of test setup

Test setup		Pullout load P, kN	Bond strength f_b, MPa
Current test		14.42	3.77
Traditional test		19.58	5.12

The results clearly indicate that the traditional well-known pullout test may overestimate the actual bond strength by up to 35%. The compressive load applied on the concrete cube seems to provide additional lateral confinement on the bar that may be responsible for failure delay.

4.2. Cyclic loading

Cyclic loading, in the form of quasi-static loading, was applied to study the degradation in bond performance and adhesion properties of used materials. It was attempted to follow the displacement history shown in fig. 20 by using the load control mode of the machine. Averagely speaking, it took about thirty seconds for one cycle's application. Only six selected materials were considered in this phase of the program due to the lack of specimens by that time. Results are tabulated in table 7.

It should be noted that all remaining specimens contained 12 mm deformed bars except for material M2. Therefore the calculated bond strength was estimated for 16mm smooth bars considering the finding mentioned earlier and assuming 20% higher bond strength for the 12 mm-deformed bars as compared to 16 mm-smooth bars. Table 7 indicates that the reduction in bond strengths vary from 0.0 to 16.7% at the most for the tested adhesives and go little up to 20.7% for cement mortar. The data hence implies that bond degradation in case of inserted bars is less pronounced as compared to new construction where bond may be drastically reduced due to cyclic loading [14].

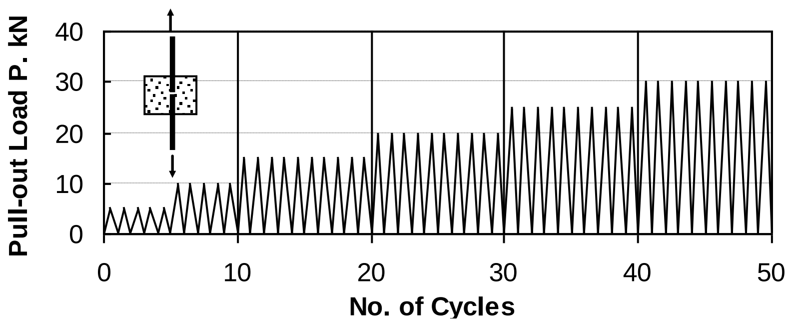


Fig. 20. Loading history.

Table 7
Effect of cyclic loading

Type of loading		Monotonic loading				Cyclic loading						Reduction in bond strength, %
Bonding Material Category	Bonding Material	Steel Bars	Ava. Pullout load P kN	Ava. bond strength MPa	Mode of failure	Steel Bars	Ava. Pullout load P kN	Ava. bond strength MPa	Bond strength for ϕ 16 MPa*	Mode of failure	No. of cycles	
Poor	M4	ϕ 16	14.42	3.77	B	Φ 12	12.74	4.38	3.65	B	11	3.2%
adhesives	Mortar	mm	23.06	6.03	B	mm	16.70	5.74	4.78	B	21	20.7%
Fair	M1	ϕ 16	25.81	6.75	C+S	Φ 12	22.30	7.67	6.39	C+S	31	5.3%
adhesives	M2	mm	29.33	7.67	C	ϕ 16	24.44	6.39	6.39	B	31	16.7%
Perfect	M3	ϕ 16	30.59	8.00	C	Φ 12	28.16	9.68	8.07	C	41	0.0%
adhesives	M7	mm	31.89	8.34	C	mm	25.0	8.60	7.17	C+S	40	14.0%

*These values are estimated by dividing the bond strength of 13mm deformed bars by a factor = 1.20.
** The effective diameter of 12 mm deformed bars used in these specimens is 12.34 mm.

In spite of this finding, other observations lead to different trend. The number of cycles attained by each specimen (fig. 21) may be a more realistic tool to compare between the materials since it directly addressee the energy introduced due to cycling. It is qualitatively shown that the numbers of applied cycles up to failure may be simply considered on the range of 20, 30, and 40 cycles for poor, fair, and perfect adhesives, respectively.

From another prospective, all modes of failure observed under cyclic loadings are either similar to or worse than those attained by comparable specimens under monotonic loadings as seen in fig. 22. As expected, the poor adhesives M4 and M5 (cement mortar) yield bond failure Material M2 that failed under monotonic loading by concrete crushing indicating good bond behaved completely different under cyclic loading and showed bond failure even when deformed bars were used (fig. 22-b). Also, the mode of failure in case of Material M7 changed but to a much lesser extent. At the mean time, Material M3 that was classified as perfect adhesive was not affected by cyclic loads (fig. 22-c).

4.3. Prototype testing

A concrete prototype was constructed to simulate a real column in a building. The cross sectional dimensions were 20 × 60 cm. The used steel bars were 10 mm-smooth bars and 16 mm-deformed bars. Holes of diameters 14 mm and 20 mm were drilled in concrete up to 13 cm to depth. Eight adhesive materials were incorporated in this phase of the program and used to fix the bars horizontally into the prototype as seen in fig. 23. The special pullout equipment shown in fig. 24; "Enerpac Hydraulic Cylinder" with ultimate capacity 32 tons was used for testing. The pullout load was recorded in bars then transformed to tons using the calibration data sheet of the equipment. Results are listed in table 8.

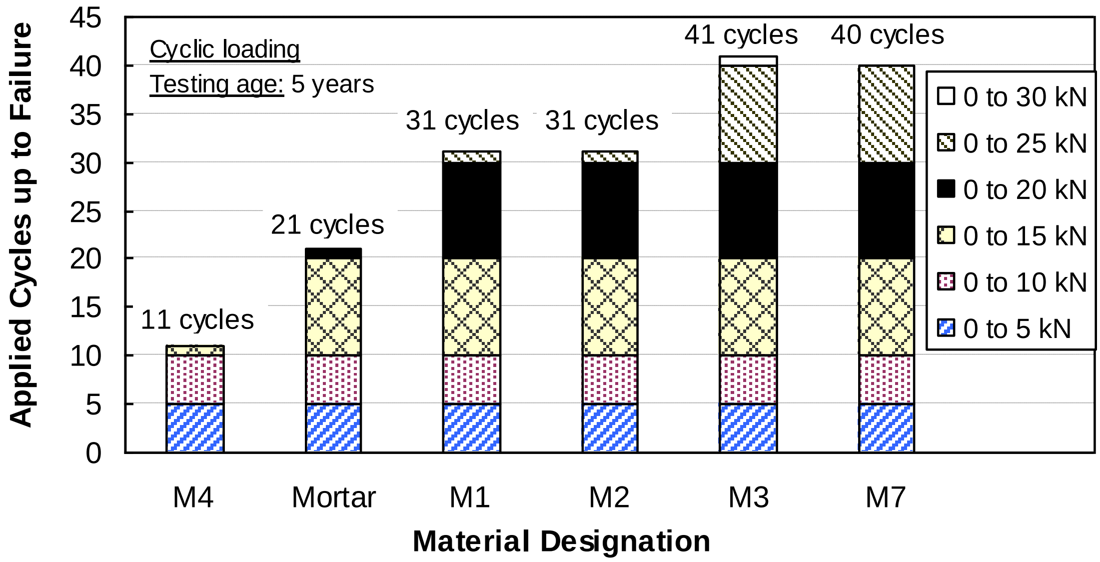
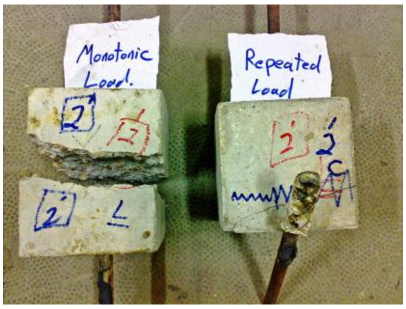
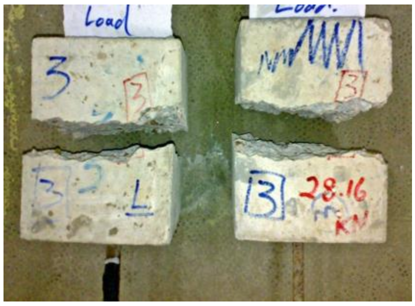


Fig. 21. Effect of cyclic loading on modes of failure.

(a) Poor behavior of M4



(b) Poor and perfect behavior of M2



(c) Perfect behavior of M3

(d) Moderate behavior of M1 and M7

Fig. 22. Effect of cyclic loading on modes of failure.

Fig. 23. Testing of concrete column prototype.

Fig. 24. The used pullout testing machine.

Table 8
Performance of different materials in practical application

Material Category	Bonding Material	10 mm-smooth bars ($\phi_{effective}$ = 9.86 mm) L, cm	Pullout load P, tons	Bond strength f_b, MPa	16 mm-deformed bars ($\Phi_{effective}$ = 15.71 mm) L, cm	Pullout load P, tons	Bond strength f_b, MPa
Poor to fair adhesives	Mortar	9.9	1.63	5.21	-	-	-
	M8	9.8	2.01	6.50	13.0	9.79	15.0
	M1	10.0	2.33	7.37	11.5	11.18	19.32
	M12	10.2	2.33	7.23	11.5	10.25	17.7
Perfect adhesives	M3	9.9	2.56	8.19	11.5	12.58	21.7
	M7	9.8	2.56	8.27	11.0	12.58	22.7
	M10	9.8	2.56	8.27	12.5	13.51	21.5
	M11	9.0	2.56	9.04	10.5	12.12	22.90

The results support the findings concluded throughout laboratory study. Again, the polyester-resin material (M8) showed inadequate performance. The perfect adhesives M3, M7, M10, and M11 achieved, with 16 mm-deformed bars, the highest bond strengths that vary from 21.5 to 22.9 MPa with an average value of 22.2 MPa. It is interesting to point out that these strength levels are considerably higher by up to 85% than those attained earlier in the lab using these materials but with 12 mm-deformed bars (average value = 11.8 MPa. This difference is attributed to the difference in test setup and to a large extent to the bar texture. It seems also that the ribs play a role in l6 mm bars under the used setup. In fact, the used pullout equipment applies compression on concrete while pulling out the bar through a narrow hole in the machine. The ribs generate forces that tend to split the concrete around the bar hence this action does not occur. This setup is similar to the traditional pullout test that is no longer effective (ASTM C234) [24] as mentioned earlier.

4.4. Proposed provision

In the light of the comprehensive data reported herein, and based on the types of adhesives and number of specimens considered in this study, the following approach is proposed for the assessment of adhesive materials commercially available. The approach considers minimum field bond strength of 20 MPa for 16 mm- deformed bars, and 8 MPa for 10 mm- smooth bars as minimum boundary for perfect bond providing the use of similar machine to that shown in fig. 24. The proposal suggests laboratory and field testing and minimum acceptance requirements as follows:

Criterion 1

"The subject adhesive is to be used in the lab to fix two 12 mm-deformed bars in high-strength 15 cm-concrete cubes (40 MPa) to form a sample similar to that prescribed herein. The adhesive may be considered adequate for repair projects if the pullout load exceeds 30 kN without the occurrence of bar pulling out from concrete".

Criterion 2

"For practical purposes, the subject adhesive is to be used in the field to fix both 10 mm-smooth bars and 16 mm-deformed bars into holes drilled horizontally up to depths 10 cm in sound concrete element at the project. The adhesive may be considered adequate for repair projects if the pullout load exceeds 25 kN, and 100 kN for the subject smooth and deformed bars without the occurrence of bar pulling out from concrete. The success of both conditions is a must for adequate performance".

Although it is extremely difficult to obtain comprehensive provision, the proposed criterion are achieved based on the number of specimens and types of adhesives reported herein and may be considered as useful guidelines. Further research is required to verify the statement mentioned above.

5. Conclusions

Based on the study reported here, the following conclusions can be drawn:

1. Proper bonding of new reinforcement with existing concrete sections becomes currently of fundamental importance to many aspects of repair projects. The need for reliable bonding material is required to ensure that the new composite is intact. Material selection should be based on test verification. The cost and materials' data sheets may give crude guide.
2. Eleven polymer adhesives commercially available for bonding new reinforcement to hardened concrete are examined. The materials are produced by nine local companies. The assessment is based on results of pullout tests that are performed on 128 specimens under monotonic and cyclic (quasi static) loadings at early and late ages. Non-traditional test setup was adopted. Subject adhesives are also examined using column prototype representing field condition.
3. Three modes of failure are observed throughout the program. The first mode is 'bond failure'; where steel bar is completely pulled out of concrete indicating poor adhesive. The second mode is 'concrete splitting failure'; where concrete cube is split vertically parallel to the direction of load application implying fair to poor bond. The third mode is 'concrete failure' where concrete cube fails into halves while steel bars remains perfectly bonded with concrete indicating perfect bond.
4. Cement mortar must not be used for bonding new reinforcement to concrete.
5. Bond behavior of considered adhesives is very different. Some examined epoxy-resins and most polyester-resins show unsatisfactory bond behavior.
6. Under monotonic loading at early ages, the promising performance is noticeable only for four epoxy adhesives (out of eight) where the bond strength using 12 mm-deformed bars exceeded 10 MPa.
7. Results indicated that for 16 mm-smooth bars, the achieved bond strength using the remaining four epoxies are very comparable with that attained using cement mortar. In fact one epoxy achieved bond strength of 3.65 MPa that is much less than that attained by specimens where cement mortar is incorporated as a bonding adhesive (5.25 MPa).
8. The compressive strength of the bonding adhesive itself, based on 50 mm-cubes, does no reflect its adhesion capability.
9. The price of bonding adhesive may play a misleading rule in selection of proper materials needed to bond steel to concrete. Unexpectedly, results clearly demonstrate that the most expensive two polymer adhesives used throughout the study (87, 160 LE/kg) give fair performance whereas the best bond performances are attained by other two adhesives that have reasonable prices (24 and 17 LE/kg).
10. Long-term results support the short-term findings. Out of the eleven adhesive materials tested throughout this program and are widely

used in the Egyptian market, only four materials are appreciated.

11. From a general prospective, polyester resins are not recommended to be used for bonding new steel to concrete.

12. Two new parameters, namely the bond index (K) and the effective bond strength (f_e), are introduced in this study for consistent assessment of bond behavior of different adhesives and may be found from the bond stress-bar slip relationships. The differences between the obtained values for Parameters (K) and (f_e) that are associated with different adhesives are pronounced. Bond Index (K) varies from 54 to 261 for two epoxies.

13. On the basis of the effective bond strength (f_e), only four epoxies are found to be promising in bonding steel to concrete.

14. The effect of bar texture on bond strength in repair work seems to be less pronounced than that in new construction. An improvement on the order of 10% at the most may be achieved when using deformed bars rather than smooth bars with comparable diameters. This finding supports the importance of proper selection of bonding material in concrete repair projects.

15. The results clearly indicate that the traditional pullout test may overestimate the actual bond strength of inserted bars by up to 35%.

16. Bond degradation due to cyclic loading for inserted bars is less pronounced as compared to new construction where bond may be drastically reduced. However, failure modes using a given bonding adhesive may be changed from concrete failure under monotonic loading to bond failure under cyclic loading

17. Results obtained from testing prototype representing concrete column in the field supports most of the findings concluded throughout laboratory study.

18. In the light of the comprehensive data reported herein, and within the range of studied material, an acceptance-performance approach for the assessment of polymer adhesives as bonding agents to bond new reinforcement to existing concrete is proposed.

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References

[1] ACI Committee 503.5R-92, "Guide for the Selection of Polymer Adhesives with Concrete", ACI Manual of Concrete Practice, Part 5, Farmington Hills, Michigan, p. 16 (2008).

[2] Permanent Committee for Egyptian Code, "The Egyptian Code for the Design and Execution of Concrete Structures (ECS 203-2007)", Cairo, Egypt (2007).

[3] ACI Committee 318, "Building Code Requirements for Reinforced Concrete and Commentary (ACI 318M)", American Concrete Institute, Farmington Hills, Michigan, p. 430 (2008).

[4] R. Poston, K. Kenser, J. McDonald, A. Vaysburg and P. Emmons, "Concrete Repair Material Performance – Laboratory Study," ACI Materials Journal, Proceedings, Vol. 98 (2), Mar.-Apr., pp. 137-147 (2001).

[5] H. Abrishami and D. Mitchell, "Simulation of Uniform Bond Stress", ACI Materials Journal, Proceedings, Vol. 89 (2), Mar.-Apr., pp. 161-168 (1992).

[6] G. Fabbrocino, G. Verderame and G. Manfredi, "Experimental Behavior of Anchored Smooth Rebars in Old Type Reinforced Concrete Buildings", Engineering Structures, No. 27, pp. 1575-1581 (2005).

[7] J. Xiao and H. Falkner, "Bond Behavior Between Recycled Aggregate and Steel Rebars", Construction and Building Materials, No. 21, pp. 395-401 (2007).

[8] R. Chapman and S. Shah, "Early-Age Bond Strength in Reinforced Concrete", ACI Materials Journal, Proceedings, Vol. 84 (6), Nov.-Dec., pp. 501-510 (1987).

[9] W. Xue, X. Wang and S. Zhang, "Bond Properties of High-Strength Carbon Fiber-

Reinforced Polymer Strands", ACI Materials Journal, Vol. 105 (1), Feb., pp. 11-19 (2008).
[10] R. Treece and J. Jirsa, "Bond Strength of Epoxy-Coated Reinforcing Bars", ACI Materials Journal, Vol. 86 (2), March-Apr., pp. 501-510 (1989).
[11] G. Balazs, "Bond Under Repeated Loading," SP 180-06, Vol. 180, Oct., pp. 125-144 (1998).
[12] J. Jose, I. Vegas and A. Ferreira, "Reinforced Polymer Concrete: Physical Properties of the Matrix and Static/Dynamic Bond Behavior", Cement and Concrete Composites, No. 27, pp. 934-944 (2005).
[13] D. Kim, S. El-Tawil and A. Naaman, "Loading Rate Effect on Pullout Behavior of Deformed Steel Fibers", ACI Materials Journal, Vol. 105 (6), Nov., pp. 576-584 (2008).
[14] ACI Committee 408.2RR-92, "Bond Under Cyclic loading", ACI Manual of Concrete Practice, Part 5, Farmington Hills, Michigan, p. 32 (2008).
[15] S. Rizkalla, R. El-Hacha and H. Elagroudy, "Bond Characteristics of High-Strength Steel Reinforcement", ACI Structural Journal, Vol. 103 (6), Nov., pp. 771-782 (2006).
[16] Y. Auyeung, P. Balaguru and L. Chung, "Bond Behavior of Corroded Reinforcement Bars", ACI Materials Journal, Proceedings, Vol. 97 (2), Mar.-Apr., pp. 214-220 (2000).
[17] A. Mansoa, L. Marquezini Jr., S. Silva, D. Pashley, F. Tay and R. Carvalho, "Stability of Wet versus Dry Bonding with Different Solvent-Based Adhesives", Dental Materials, No. 24, pp. 476-482 (2008).
[18] K. Fujikake, J. Nakayama, H. Sato, S. Mindess and T. Ishibashi, "Chemically Bonded Anchors Subjected to Rapid Pullout Loading", ACI Materials Journal, Vol. 100 (3), May., pp. 246-254 (2003).
[19] R. Barnes and G. Mays, "The Transfer of Stress through a Steel to Concrete Adhesive Bond", International Journal of Adhesion and Adhesives, No. 21, pp. 495-502 (2001).
[20] ACI Committee 503R-93, "Use of Epoxy Compounds with Concrete", ACI Manual of Concrete Practice, Part 5, Farmington Hills, Michigan, p. 28 (2008).
[21] A. Elkurdi, S. Khoury and A. Ali Abdo, "Evaluation of New-Concrete Bonding Agent Systems by Slant Shear Test", Fifth Alexandria International Conference on Structural and Geotechnical Engineering (AICSGE 5, Structural Engineering Department, Alexandria University, Alexandria, Egypt, pp. MT 205-219 (2003).
[22] A. Mohamed and L. Clark, "Bond Behavior of Low-Strength Concrete, "Magazine of Concrete Research", Vol. 44 (160), pp. 195-203, Sept. (1992).
[23] A. kurdi and S. Khoury, "Rational Approach to Predict Bond Strength of Steel Bars in Concrete with and without Silica Fume", First International Conference on Civil Engineering, Helwan University, Cairo, Egypt, March, pp. 543-560 (1998).
[24] Former ASTM C 234-71, "Comparing Concretes on the Basis of the Bond Developed with Reinforcing Steel", Annual Book of ASTM Standards, American Society for Testing and Materials (1994).

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