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Strength and Durability of Adhesive Anchor Bolts

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ABSTRACT. This paper presents results of a study on adhesive anchor bolts exposed to varying and diverse environmental conditions. Pull-out tests were performed on standard concrete cylinders anchored with adhesive bolts. The anchor bolts were placed either vertically or horizontally in the concrete cylinders. Concrete cylinders were stored in their respective positions and exposed to various diverse environmental conditions. The environmental exposure and anchor placement position effects on anchor bolt load carrying capacity and slip were evaluated. Generally, the pull-out load for vertically placed anchors were higher than those for horizontally placed anchors. Specimens stored under water and exposed to freezing and thawing cycles showed the lowest pull-out resistance. In addition, the amount of slip at failure pull-out load was more for vertically placed anchors.

1. Introduction

Adhesive anchor bolts are commonly used for repairs and rehabilitation on concrete structures such as buildings and bridges. The environmental conditions, in which rehabilitation take place and their effect on the repair materials and methods, is important to the success and durability of the repair. The normal procedure for installing adhesive anchors is by drilling in hardened concrete. The diameter and depth of the drilled hole are usually predetermined by the manufacturer based on the anchor bolt diameter. Adhesive mortar is then placed in before the anchor insertion. Curing period must pass before the anchors are loaded. ACI Committee 349-80 (Appendix B) and its amendments provide the basis for all steel embedment design and testing[1].

There are four ways in which anchor system can fail: (a) Failure of the concrete mass, (b) Failure of anchor, (c) Failure along adhesive concrete interface, and (d) Failure along adhesive anchor interface; the first and last being the most unlikely modes of failure. The introduction of adhesive mortar in connection with the anchoring system helps greatly in accelerating the repair procedures. Short curing time, high carrying load capacity and precise application, are the main advantages. No specific design standards are available for grouted anchors. ACI 349 Appendix B requires the grouted anchor to meet the embedment requirements and to be tested for verification. Load transfer between anchors and concrete depends on the following[2] :

1. Mechanical interlock on the adhesive concrete interface.
2. Chemical bond between adhesive and concrete.
3. Mechanical interlock between anchor and adhesive.
4. Chemical bond between adhesive and anchor.

Adhesive mortar is composed of an epoxy adhesive plus quartzite sand. This combination embeded inside concrete and exposed to highly fluctuating temperature is thought to create a problem of durability. This problem comes from the thermal incompatibility of the components within the system. Steel, concrete, quartz and epoxy have different thermal expansion coefficients. By fluctuating the exposing temperature, expansion and contraction of different magnitudes will occur. The ultimate effect of this process can be translated into strength and durability losses. The considerable difference in coefficient of thermal expansion between epoxies and portland cement concrete requires careful consideration. The higher modulus of elasticity of concrete tends to restrain the movement of the epoxy causing severe stresses at the interface due to temperature changes. Sand filled epoxy is used to overcome the problem of thermal incompatibility[3].

Anchors in concrete have received a great deal of attention, especially under static tensile loading[2,4,5]. Lynch and Burdette[6] reviewed some of the basic principles of anchor behavior in tension and in shear. Their study focused on the spacing effect, shear directed toward free edge, and the interaction of shear and tension. They presented several design consideration for several anchor types. Kliger and Burdette[7] investigated the research needs in design of anchorage in concrete. Models for capacity as governed by pull-out assuming uniform tensile stress acting perpendicular to the failure cone surface satisfactorily correlate with test results, but shows considerable scatter. The prediction of pull-out resistance of partial cones is more scattered than for a complete one. Siddiqui and Beseler[8] presented charts to assist designers in computing the concrete pull-out strength for multiple anchor bolt configurations. Most of the literature and design criteria focused on the use of cast in place anchors. In general, grouted adhesive anchors received less attention. Moreover, the effect of adverse environmental exposure, on the behaviour of adhesive anchor bolts received little or no attention. The anchors were inserted in two positions, vertical (V) and horizontal (H) to simulate some of their use in practice. In the very early stages, the uniformity of epoxy adhesive distribution around the anchor and its thickness is influenced by the placement position. Non-uniform adhesive distribution surely will effect the pull-out strength of the anchor bolt. The aim of this paper is to present the findings of the research carried out on adhesive anchors exposed to diverse environmental conditions for periods up to 30 weeks. In addition, the effect of placement positions (V and H) on pull-out strength is reported.

2. Research Significance

The principal objectives of the research presented here were :

a) To examine the influence of different environmental exposure conditions on the load carrying capacity and maximum slip level of adhesive anchors.

b) To examine the influence of specimens repair and storage positions (horizontal and vertical) on load carrying capacity and slip measurements.

c) To examine the influence of exposure conditions, repair and storage positions on the load-slip characteristics of concrete-adhesive interface or adhesive-anchor interface.

Since adhesive anchors can be used in various construction exposed to various environmental conditions. It is significant to show that the pull-out loads were the lowest for anchors placed in concrete and stored in water and exposed to freezing and thawing cycles. It is also significant to report that the pull-out loads for horizontally placed and stored anchor specimens were generally less than the pull-out loads for vertically placed and stored anchor specimens. The anchor placement and storage position effect are important in the sense of assuring even thickness of the repair materials around the anchor, especially at early stages of applying the adhesive grout, Fig. 1. The ductility, measured in terms of ultimate slip at failure, of the horizontally placed and stored anchor specimens were found to be less than those for vertical ones which can be an important factor in determining anchor failure characteristics. Finally, the data compiled for this study can be used to fill the gap in understanding the behaviour of epoxy grout adhesive anchors exposed to various environmental conditions.

3. Outline of the Experiments

Standard concrete cylinders 150 mm × 300 mm (6 in. × 12 in.) were made. The average 28*th* day compressive stress for concrete specimens tested was 3200 psi (224 Kg/cm^2). Forty four cylinders were drilled in the center using a diamond drill bit. The drill hole was cleaned with compressed air. The two sections glass tube containing epoxy-acrylate resin hardener and quartz sand was then inserted in each of the drilled hole. Finally the anchor rod was driven into the adhesive cartridge causing to break the glass tube and initiate the hardening of the resin. The anchor shank diameter and embedment length were 16 mm and 125 mm respectively.

In the experimental programme variables were chosen to examine the effect of time and exposure conditions (temperature and moisture) on the pull-out load and anchor slip. In addition, the effects of placement and storage positions (horizontal or vertical) on the pull-out load and anchor slip were examined.

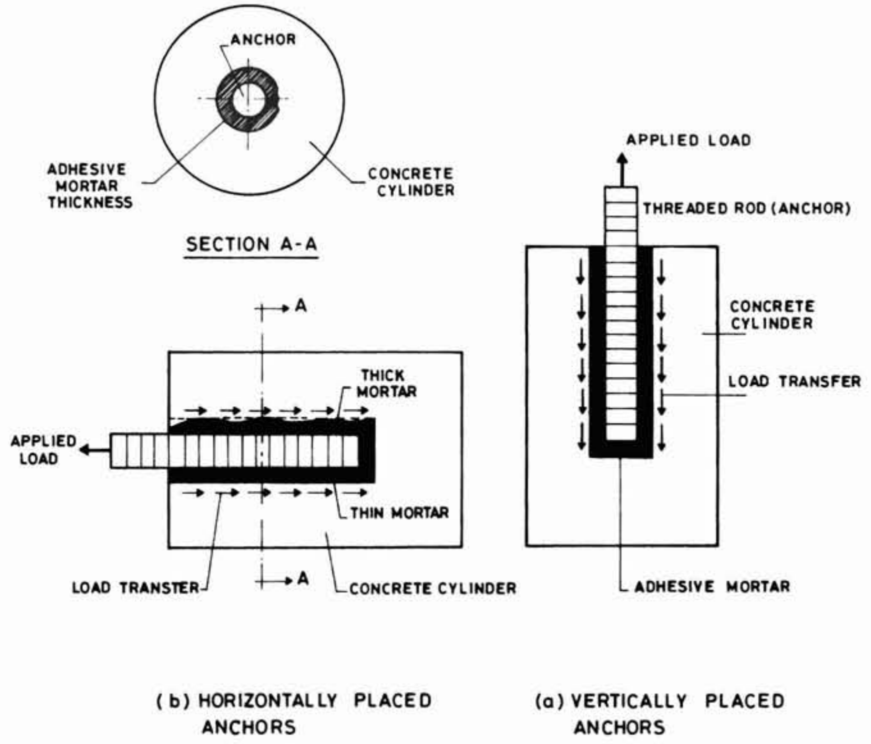

FIG. 1. Anchor placement positions.

3. Experimental Details

Table 1 gives a summary of the specimens made and their respective exposure environments. Three environmental rooms with different temperature settings were used. The maximum temperatures chosen were 60, 30 and 0°C. Half of the specimens placed in the 0°C temperature were put under water with the other half left dry. The maximum temperatures chosen were allowed to drop or climb to 26°C daily. In other words gradually the temperatures were allowed to cycle between the set temperature and 26°C once every twenty four hours. Furthermore, one set of specimens was placed under water and in room temperature (26°C). Another set was placed outside in the natural environments and exposed to solar heat which measured to be in excess of 55°C on concrete surface at day time and dropped to about 24°C at night.

Specimens were tested at intervals of 7, 9, 12 and 30 weeks.

4. Experimental Results

The results are presented in a series of graphs and tables to highlight the relationship between the various variables in their measured properties.

TABLE 1. Maximum pull-out load (kN).

Exposure condition	Specimen designation		Time in weeks			
			7	9	12	30
0°C to 26°C	A	V	58	45	45	54
		H	29	54	–	46
0°C to 26°C underwater	B	V	53	35	39	38
		H	39	35	49	35
30°C to 26°C	C	V	55	78^*	64	48
		H	45	46	–	58
60°C to 26°C	D	V	55	73	55	53
		H	56	64	–	48
26°C to underwater	E	V	53	–	–	50
		H	52	–	–	45
Outside conditions	F	V	74	61	72	45
		H	56	66	43	45

(*) = Failure of the shank.
(*V*) = Vertically placed anchors.
(*H*) = Horizontally placed anchors.
(–) = No specimen tested.

Tables 2 and 3 represent the maximum slip and ratio of ultimate pull-out load to load at 1.00 mm slip.

Figure 2 shows the pull-out load (kN) drawn against time in (weeks) for vertical steel anchors in concrete placed at the 0°C to 26°C cycle temperature compared with specimens stored at 26°C. The specimens were vertically placed and stored. It can be seen that the pull-out load for anchors stored in water and exposed to freezing and thawing cycles resisted the lowest pull-out load. Anchors exposed to cyclic temperatures but kept dry resisted practically the same pull-out load as those anchors stored in 26°C constant temperature.

Figure 3 presents the pull-out results of steel anchors versus time for specimens placed and stored horizontally. The anchors placed under water and exposed to the 0°C to 26°C cycled temperatures offered the least resistance to pull-out load. This agrees with the results obtained for vertically stored specimens. From the figure, greater inconsistency in the pull-out load with time is observed. This is probably resulted

TABLE 2. Maximum slip (mm).

Exposure condition	Specimen designation		Time in weeks			
			7	9	12	30
0°C to 26°C	A	V	5.2	3.5	3.8	5.2
		H	2	4	-	4.2
0°C to 26°C underwater	B	V	2.8	3.4	2.5	3.6
		H	2.7	2.5	2.8	3.4
30°C to 26°C	C	V	4.5	5.5	5.5	6.5
		H	2.4	3.8	-	5.5
60°C to 26°C	D	V	3.5	4.3	3.9	3.8
		H	4.5	4.5	-	3.6
26°C to underwater	E	V	3.5	-	-	7.2
		H	3.6	-	-	4.2
Outside conditions	F	V	5.2	3.8	5	3.6
		H	3.6	4.6	3.1	3.2

(*V*) = Vertically placed anchors.
(*H*) = Horizontally placed anchors.
(–) = No specimen tested.

from the uneven distribution of the epoxy adhesive around the anchor bolts. Except for the inconsistency mentioned above, Fig. 2 and 3 showed similar trends.

Figure 4 gives the results for anchors exposed to outside environment and 60°C, 30°C, 26°C fluctuations temperatures for vertically stored specimens. The results show that, with time and temperature fluctuations, the pull-out load is reduced. At thirty weeks, the pull-out load became practically the same for all specimens exposed at various environmental conditions. Large scatter can be observed in early testing periods. The major cause of the scatter is that at the early testing age, concrete hydration is accelerated by the heat treatment causing it to achieve higher compressive and tensile strengths. Continuing the heat cycle causes the concrete and the adhesive to be exposed to fatigue and may develop hair cracks and bond loss at the interface. The anchor pull-out load is assumed to be highly dependent on the concrete tensile strength. Reduction in concrete tensile strength and deterioration of the bond at the interface is believed the cause of reducing the pull-out load at later testing age (30 weeks).

TABLE 3. Ratio of ultimate pull-out load (kN) to load (kN) at 1.0 mm slip.

Exposure condition	Specimen designation		Time in weeks			
			7	9	12	30
0°C to 26°C	A	V	7	2	2.5	8
		H	2	4	–	7
0°C to 26°C underwater	B	V	2.4	4.4	2.2	4.8
		H	4	2.7	4	4.4
30°C to 26°C	C	V	4.4	6	6	12
		H	3.8	9.2	–	3.6
60°C to 26°C	D	V	2.6	3.4	4.7	2.7
		H	5.6	6.4	–	3.4
26°C to underwater	E	V	3	–	–	10
		H	3.5	–	–	5
Outside conditions	F	V	3.5	3.3	6	5.6
		H	4.7	4.4	5	2.8

(*V*) = Vertically placed anchors.
(*H*) = Horizontally placed anchors.
(–) = No specimen tested.

Figure 5 is similar to Fig. 4 but for horizontally placed and stored specimens. It is clear that specimen exposed to 30°C temperature increased resistance with time. For the other specimens resistance decayed with time. The decay in pull-out load resistance with time as presented in Fig. 4 and 5 is pronounced if we consider the fact that the pull-out resistance was limited by burst of concrete cylinders. The bursting load is a function of the tensile strength of concrete. That tensile strength expectedly will increase with ageing of concrete. Thus a higher pull-out load is expected for aged specimens if exposure conditions were favourable. The pull-out loads for horizontally placed anchors, under the various exposure conditions at 30 weeks, showed higher scatter than that for vertically placed anchors caused probably by the uneven distribution of the epoxy grout around the anchor bolt.

5. Observations on the Load-Slip Results

Figures 6 and 7 show the relationships between normalized pull-out load and normalized slip at 1.0 mm. The relationship is almost linear with higher scatter for hori-

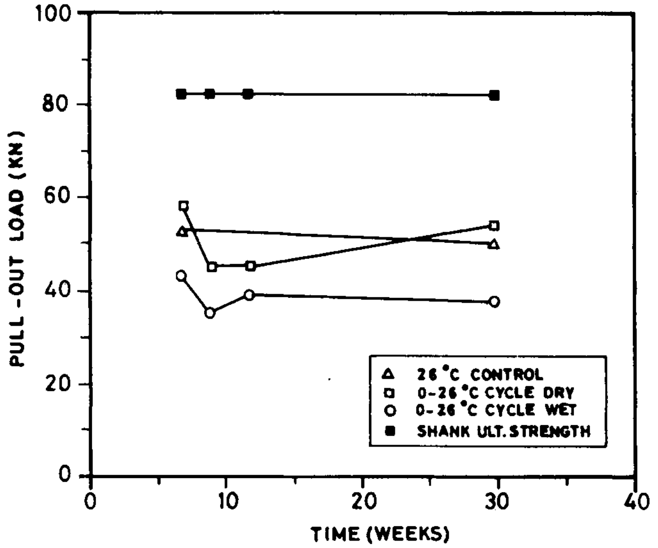

FIG. 2. The relationship between the pull-out load and time for specimen placed and stored vertically.

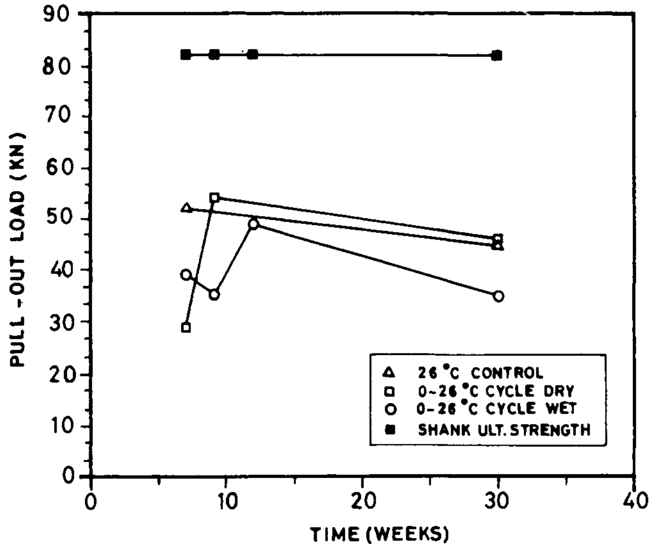

FIG. 3. The relationship between the pull-out load and time for specimen placed and stored horizontally.

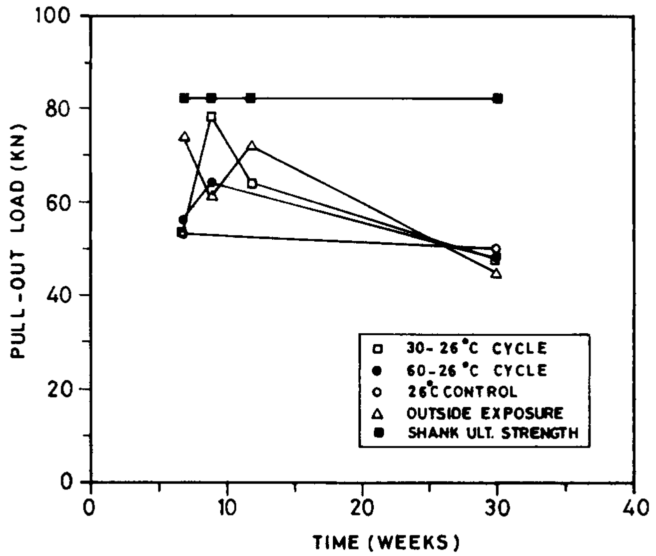

FIG. 4. Relationship between the pull-out load and time for specimen placed and stored vertically.

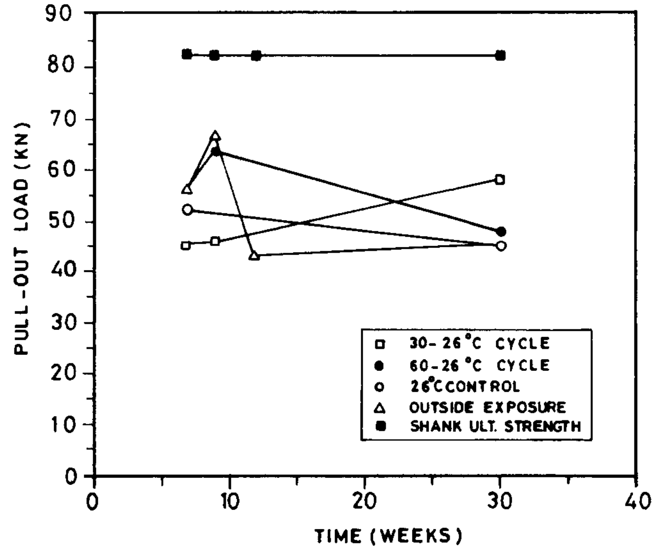

FIG. 5. Relationship between the pull-out load and time for specimens placed and stored horizontally.

zontally placed and stored anchor specimens. For vertically placed and stored anchors, the normalized pull-out loads and slips ranged from 2 to 12 and 2.8 to 7.2 respectively. For horizontally placed and stored anchors, the normalized pull-out loads and slips ranged from 2 to 10 and 2.0 to 5.5 respectively.

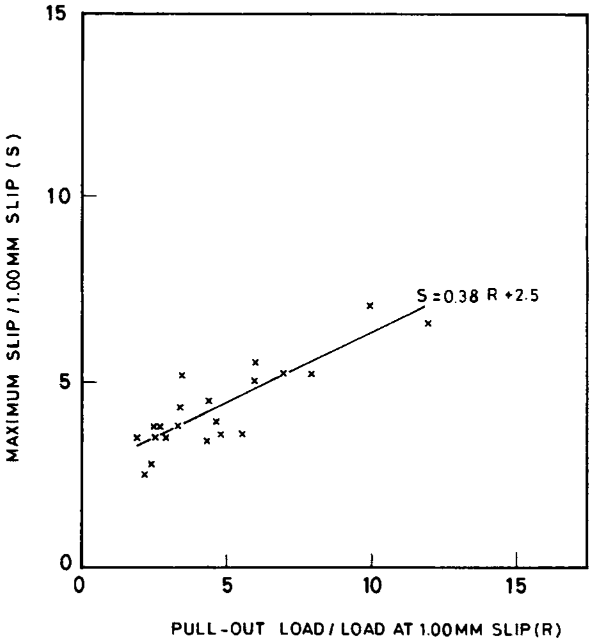

FIG. 6. Relationship between the normalized pull-out load and normalized slip at 1.0 mm for vertically placed and stored specimens.

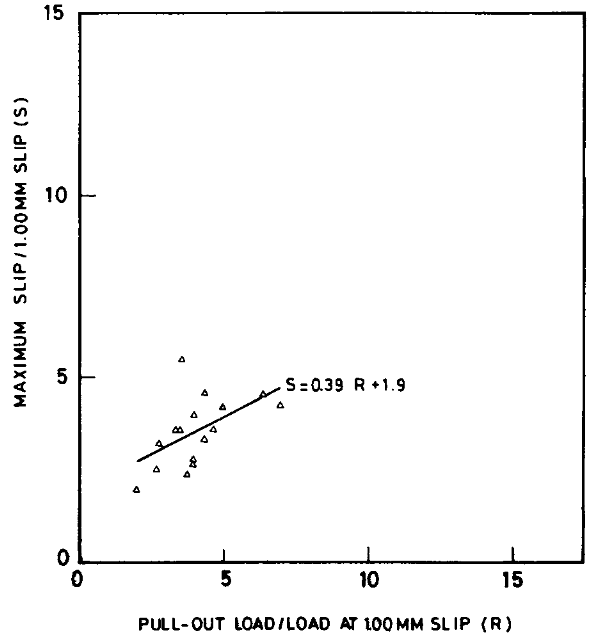

FIG. 7. Relationship between the normalized pull-out load and normalized slip at 1.0 mm for horizontally placed and stored specimens.

The slip at failure pull-out load is generally higher for vertically placed and stored anchors. The author believes that this was caused by the even distribution of the epoxy adhesive in the case of vertically placed anchors. This even distribution caused the whole embedded length to resist the applied load over the entire bolt surface area. However, for horizontally placed and stored anchors a reduction effect similar to that of bond in top steel reinforcement might have occurred. Depending on the space between the drilled hole and the anchor bolt, it is fair to assume that a thin layer of epoxy adhesive would exist underdeath the bolt and a thicker layer over it. Moreover, due to the fluidity of the adhesive at the early stages of application, the concrete-adhesive contact surface would not cover the entire embeddment length over the anchor. Hence, the adhesive uneven distribution would cause localized bonding failures along the embeddment length. These bonding failures caused the horizontally placed anchors to fail at lower loads and lower slips. This was true for all horizontally stored specimen. Finally, it worth noting that the load required to produce 1 mm slip decreased with exposure time in the majority of the tested specimens.

Table 4 represents the areas under complete load-slip diagrams. The lowest load-slip areas were computed for the anchors exposed to freezing and thawing cycles. For the rest of exposure conditions, vertically placed and stored anchors generally give higher load-slip areas than those calculated for horizontally placed and stored anchors.

Figures 8 and 9 show the relationships between the pull-out loads (kN) and the areas under load-slip diagrams for vertical and horizontal placements and storing positions respectively. The relationships are linear. The load and load-slip areas for vertically placed and stored anchors ranged from 35 to 78 kN and 54 to 266 kN-mm. The pull-out loads and load-slip areas for horizontally placed and stored anchors ranged from 29 to 66 kN and 34 to 174 kN-mm.

Figure 10 shows the pull-out load drawn against the areas under-slip diagram taken as percentages of their respective pull-out loads. The relationship is found to be linear and best fit lines for both vertical and horizontal placed and stored coincided. Higher loads and larger slips produced higher load-slip areas. The load-slip areas represent the toughness area which is a measures of energy absorption and in turn ductility. With the above knowledge and Fig. 10, one can reach the conclusion that vertically placed and stored anchors behave with more ductility at failure than horizontally placed and stored anchors.

6. Conclusion

The following can be concluded :

1) The pull-out load for anchors from concrete specimens stored in water and exposed to freezing and thawing cycles was the lowest compared with the loads for specimen stored at other temperature settings.

2) The relationships between normalized slip and normalized pull-out load are linear for specimens placed and stored either vertically or horizontally. Vertically

TABLE 4. Areas under slip load diagram (kN-mm).

Exposure condition	Specimen designation		Time in weeks			
			7	9	12	30
0°C to 26°C	A	V	136	63	71	96
		H	34	120	–	86
0°C to 26°C underwater	B	V	69	56	54	63
		H	56	42	90	55
30°C to 26°C	C	V	163	266	193	169
		H	54	87	–	174
60°C to 26°C	D	V	110	181	132	90
		H	119	147	–	91
26°C to underwater	E	V	102	–	–	221
		H	101	–	–	98
Outside conditions	F	V	251	120	193	86
		H	94	155	74	73

(*V*) = Vertically placed anchors.
(*H*) = Horizontally placed anchors.
(–) = No specimen tested.

placed and stored anchors resisted higher loads and failed at larger slips compared with those anchors placed and stored horizontally.

3) The relationships between area under load-slip diagram and pull-out load are linear for both vertical and horizontal placed and stored specimens. The load-slip areas for vertically placed stored anchors were larger than those for horizontally placed and stored anchors. The areas under load-slip diagram measures the toughness and in turn the energy absorbed until anchor separates from test specimen. With this in mind, it can be said that vertically placed and stored anchors failed in a more ductile mode than horizontally placed and stored ones.

4) Horizontally placed and stored anchors showed more scatter in their pull-out loads. This is believed to be due to the non-uniform adhesive distribution around the horizontally placed anchor bolts. The uneven adhesive distribution caused the interfacial bond to fail locally thus causing lower pull-out loads and lower measured slips.

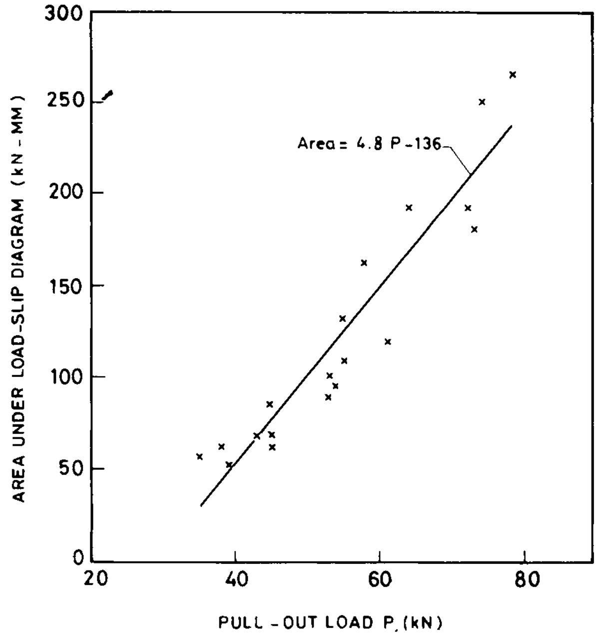

FIG. 8. Relationship between the pull-out load and area under load-slip diagram for vertically placed and stored specimens.

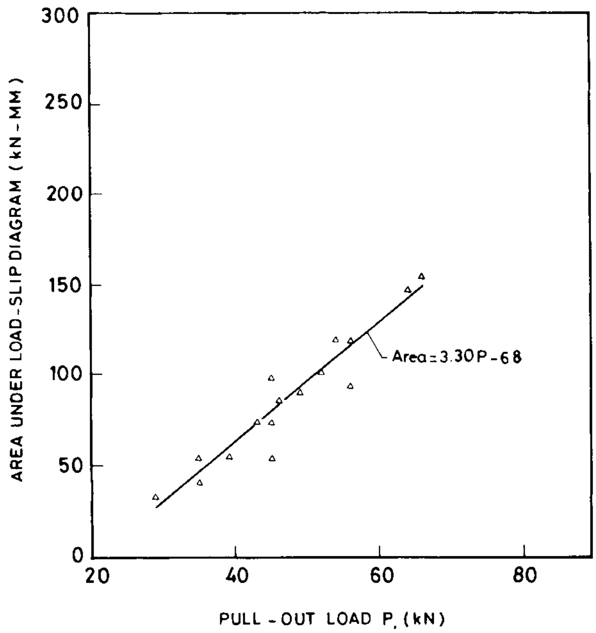

FIG. 9. Relationship between the pull-out load and area under load-slip diagram horizontally placed and stored specimens.

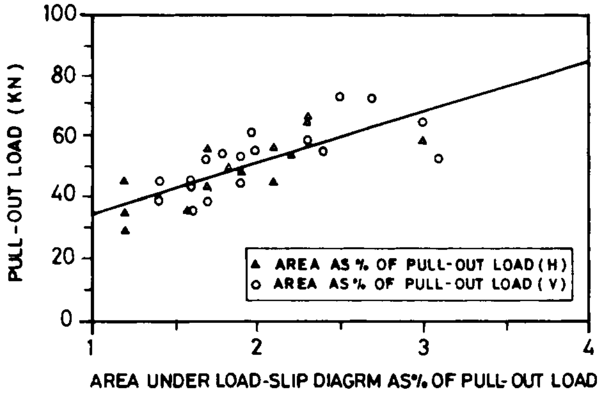

FIG. 10. Relationship between the pull-out load and area under load-slip diagram taken as a percentage of their pull-out loads for both horizontally and vertically placed and stored specimens.

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تحمل ومتانة مسامير التثبيت اللاصقة

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المستخلص . هذا البحث يعرض نتائج دراسة تأثر المسامير اللاصقة عند تعريضها لظروف مناخية صعبة ومختلفة . لقد تم إجراء اختبارات الشد على مسامير لاصقة مغروسة في أسطوانات خرسانية . وقد غرست هذه المسامير رأسيًا أو أفقيًا وتم خزنها وتعريضها بنفس الأوضاع لظروف وعوامل جوية مختلفة . وبناء على نتائج الاختبارات فقد تم تقييم تأثير الظروف المختلفة ووضع العينة على قدرتها على مقاومة أحمال الشد وقيمة الانسحاب الأقصى . وأثبتت النتائج بشكل عام تفوق المسامير اللاصقة المغروسة رأسيًا على تلك المغروسة أفقيًا من حيث قدرتها على مقاومة أحمال الشد وقيمة الانسحاب الأقصى . كما أثبتت النتائج أن المسامير اللاصقة المعرضة للتجمد والذوبان أبدت أقل قدرة لمقاومة أحمال الشد .