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Experimental investigation of behaviour and failure modes of chemical anchorages bonded to concrete

Özlem Çalişkan *, Murat Aras

Bilecik Şeyh Edebali University, Department of Civil Engineering, Bilecik, Turkey

HIGHLIGHTS

- Different adhesive types.
- Anchorage diameters.
- Embedment depth.
- Strength of anchors were calculated according to ACI 318 (2008).
- Capacity equation proposed.

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ABSTRACT

In this study, the effect of using different adhesive types, anchorage diameters and embedment depth on the tensile strength of the anchors were evaluated. In the experimental work, concrete blocks on which the anchor was embedded were unreinforced and had a compressive strength of 25 MPa. The ribbed construction iron bars with 12, 16, 20 and 24 mm diameter were selected to be used as anchors. The depth of embedding is determined to be 5, 10, 15 and 20 times the diameter of the used anchors. The holes, to which the anchors were embedded, were 4 mm larger than the anchor's diameter. 10 different types of chemical adhesives were used in the study. These adhesives are based on 4 epoxy, 3 polyster, 2 epoxy acrylics and 1 vinylester. By using the load-displacement graphs obtained from this study, axial load capacity, failure modes, initial stiffness, displacement ductility ratios and energy dissipation capacities were calculated and important conclusions were obtained from discussing the experimental results regarding the general performances of anchors. Also, capacity and design strength of anchors were calculated according to ACI 318 (2008). As a result, the effect of the chemical adhesive usage on the anchors performance was evident in the anchors with diameters of 16, 20 and 24 mm while, at small diameters, the effect wasn't clear also the best durability was obtained when using epoxy-based adhesives, and the ideal embedding depth was 16 mm for 10Φ anchors and 20 and 24 mm for 15–20Φ anchors.

1. Introduction

Bonding of chemical anchors occurs due to the friction force of chemical agent between concrete and anchorage bar [5]. Characteristic properties of chemical agent used in the chemical anchors must be determined to provide full bond [21]. It is a known fact that usage area, usage style, environmental conditions and quality of workmanship are effective factors on the axial tensile resistance of anchors [8].

The mechanism of connecting the new element to the present structural element can be accomplished by using mortar or chemical anchor types [2]. The recent years have shown an increase rate in the usage of chemical adhesives for installing anchors, and this led to increase the important of the adhesive types. From the first design made for chemical anchors [2] and [23]) till today, many studies have been done. A great majority of these works were directed to determine the pulling behavior of anchors [9,17–20,24,25,29]. Other studies had investigated the behavior of anchorage with or without heading with different adhesive types mortar or chemical) in uncracked or cracked concrete blocks [4,6,13]. In literatures, there are studies available for estimating the axial pulling capacity by means of design approaches, mathematical models, proportional design and algorithms [11]. Studies were also carried out to specify the axial pulling behavior with different parameters including; environmental

* Corresponding author.
E-mail address: ozlem.caliskan@bilecik.edu.tr (Ö. Çalişkan).

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effects, failure type estimations, different edge distances and distances between the embedded anchors [7,11,14,15,17]. Bajer and Barnat [4] studied the behavior of the most commonly used chemical adhesive types like vinyl, polymer-cement and epoxy resin in the interface between concrete and high strength steel material. In hardened concrete, pull out tests were carried out using two types of epoxy resin and cast mortar with different anchorage diameters [12,22]. Wang et al. [28] examined the axial tensile behavior of anchoring elements (grooved and plain bar) with grout mortar, large diameter (36, 48, 90, 150 mm) and different hole diameters (46, 58, 100, 160 mm). The grooved anchors have shown larger axial pull-out capacities in comparison to plain anchors. Tondolo [26] has studied the effect of corrosion on the anchorage strength. As a result of the study, he stated that the strength values fell suddenly after 2% corrosion. Elices et al. [10] investigated the mechanical changes on different types of anchor bars after prestressing by using electron microscopy. Their observations showed that increasing the fracture toughness of the anchor bars made them more resistant to damages. Ivorra et al. [16], examined the application of anchorage experimentally and analytically in natural stone of facade cladding, they concluded that natural stone panel thickness and wind load are important. Turker et al. [27] showed that the bars placed next to the anchor directly influence the axial tensile resistance of anchor.

According to the previous studies mentioned above, it is obvious that the changing, renewing and increasing of chemical adhesives types properties should be examined. There are many variables affecting the strength of the embedded anchors in precast concrete such as; anchor's diameter, the drilled hole's diameter, embedment depth, the existing concrete strength, humidity, ambient temperature, surface cleanliness, distance between the anchorage, the distance of the anchors from the edge and the type of the adhesive. These variables were taken into consideration in the present work as well as the drilled holes were kept free from moisture and dust. The edge distances and the distances between anchors were specified considering the limitation mentioned in ASTM-E 488 [3]. The changing of anchors diameter 12, 16, 20 and 24 mm), anchors embedment depth 5, 10, 15 and 20 times the diameter) and the usage of 10 different types of chemical adhesives 4 epoxies, 3 polyesters, 2 epoxy acrylics and 1 vinylester based) were investigated in the experimental study. According to ACI 318 [1] the bearing strength of the anchors were analytically calculated and interpreted in comparison with the obtained experimental results.

2. Experimental study

2.1. Test specimens and material properties

In the experimental study, unreinforced concrete blocks were produced for the placement of the chemical anchors which were representing by the using of ribbed steel bars used in construction works. The average cubic concrete compressive strength of 28 day was 25 MPa. Within the scope of the study, the anchors diameter was 12, 16, 20 and 24 mm, the embedment depths were 5, 10, 15 and 20 times the anchor's diameter. The edge distances and the distances between anchors were specified according to ASTM E488 standard. The dimensions of concrete block manufactured for test specimens with anchorages of 24 mm diameter and 480 mm embedment depth was given in Fig. 1. The compressive strength of concrete blocks was design as 25 MPa. All concrete blocks were cast simultaneously with identical mix. 5 standard cube specimens for each concrete blocks were cured and conserved with identical conditions in test specimens. These cube specimens were tested simultaneously with the test specimens and used to measure the compressive strength of concrete blocks. The average compressive strength of test specimens was measured as 27.4 MPa with a very low standard deviation. The mix design of concrete used for the concrete blocks is given in Table 1.

The chemical adhesives properties used in the present study (material structure, density and compressive strength) are given in Table 2. These values were specified by the manufacturer companies. Care has been taken in during the selection and application of the adhesive materials. 4 of the chemical adhesives used are epoxy, 3 polyester, 2 epoxy acrylic and 1 vinylester. 10 chemical anchors were used, 9 of them in the cartridge with 2 component materials. Only 1 of the anchors is made of three components and the mixture was made by the practitioner. Some of the specimens prepared for testing are given in Fig. 2. The properties of the tested elements, the studied variables and tests results are summarized in Table 3. In this study, the anchor diameter is denoted by D (mm), the depth of insertion L (cm) and the adhesive material by M. For example, in element D12L6, the diameter is 12 mm and the embedding depth is 60 mm. In scope of the experimental study, 10 different types of adhesives of 3 different companies were tested. Compounds of these adhesives include four different material structures. The main reason for selecting these adhesives is the observation from the literature that they are commonly used in the anchorage applications. The only variable tested in the study was not the adhesive type, but the anchorage diameter and embedment depths were the other parameters. Also the interaction of these parameters investigated in the study.

The diameters of the holes drilled for the anchorages were 4 mm larger than the diameters of anchorages. This application was provided space for 2 mm thick adhesive layer in both sides of anchorages. The holes were drilled smooth and straight, and they are cleaned with pressurized air. Holes without any dust and humidity were filled with adhesive then the anchorages were embedded to the holes. The tests were performed after 7 days of the placement of anchorages to provide the full strength of adhesives.

2.2. Test setup and instrumentation

In the experimental part of the work, an axial tensile test (pull-out) was applied to the anchorage elements in concrete blocks. The axial tensile load was applied to the tested anchors by using of a portable loading bridge with a hydraulic loading system installed on the concrete block on which the anchors were installed. The test setup and the schematic representation are given in Fig. 3. During the tests, the load was applied by using 500 kN capacity Load cell while the axial deformation was measured by a 50 mm capacity electronic displacement gauge (LVDT). The load was applied with a 500 kN capacity and 150 mm stroke hydraulic jack. The applied load and the axial deformation of anchors were recorded with a computer controlled data collection system. During the installation of the anchors and before applying the chemical adhesive, the surface which will be in contact with the chemical adhesive material was prepared to be free from moisture and dust to prevent the effect of the external condition. The process of dust removing was carried out by cleaning the drilled holes with compressed air. The chemical adhesive was applied to the cylindrical hole with the help of an injection gun so that there is no space left after that, the anchor was installed and left for 24 h for setting.

3. Experimental result

3.1. Observation and general failure mode

The load-displacement graphs were drawn for each of the tested samples followed by comments regarding the anchors performance depending on load-displacement graphs. By using the load-displacement graphs of the tested elements, the maximum axial tensile strengths, initial stiffness, displacement ductility ratios and energy dissipation capacities were calculated. The results obtained from the experimental study are given in Table 3. Furthermore, interpretations for the chemical anchors behavior and failure mechanisms were made depending on the resulted failure mechanisms and the general load-displacement behavior. Examples of selected load-displacement graphs obtained from the experimental study are shown in Fig. 4, while Fig. 5 shows failure mechanism for some of the tested specimens.

3.1.1. 12 mm diameter anchors

When the experimental work evaluated in terms of the anchor diameter, it could be notes that the anchor with a 12 mm diameter and 60 mm embedment depth had lowest strength value of 14.80 kN when using material M6, and had highest strength value of 28.90 kN when using material M10 which consisted of three components and mixed by the practitioner. Material M10, showed the highest strength values for 60 mm embedment depth and lowest value for other depths. The average tensile capacity for anchors which had 60 mm depth and have been installed with 10 different types of adhesives was 21.9 kN. 5 materials were below this average value. Also during the examination of failure modes, concrete breakout types were observed for all specimens.

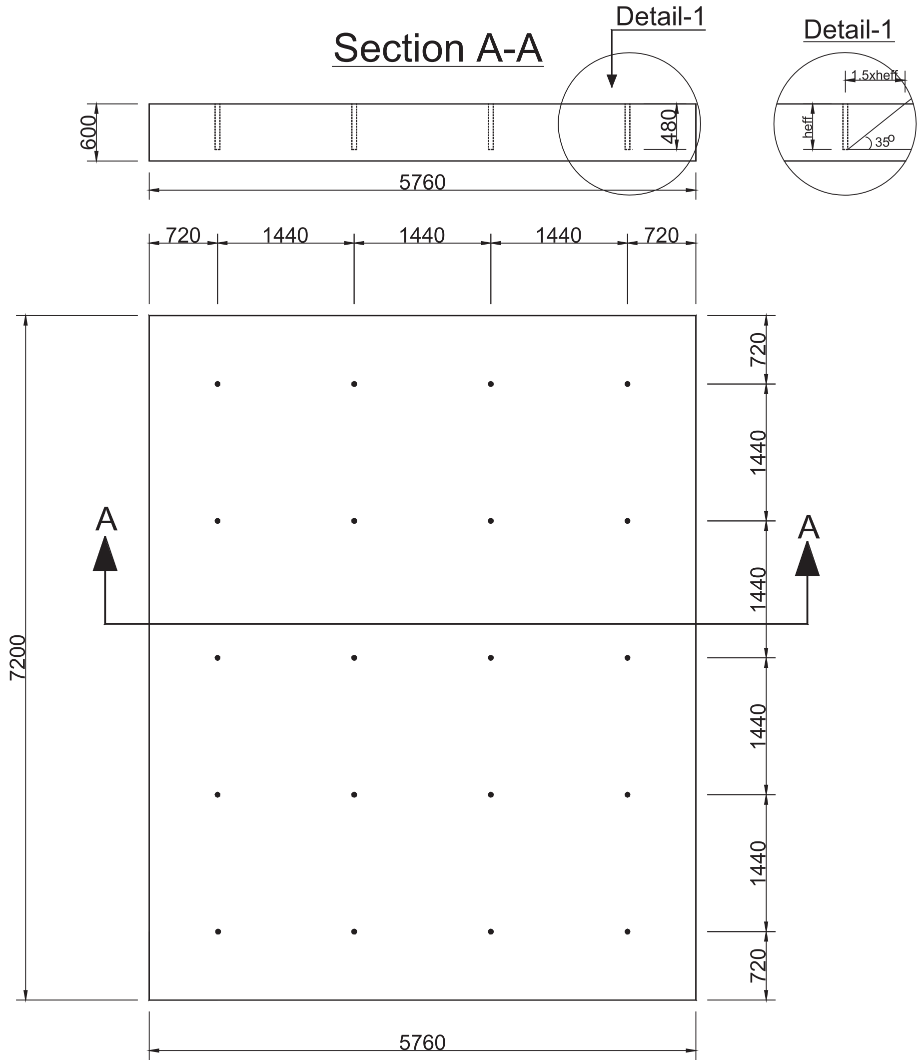


Fig. 1. Concrete block dimension for 24 mm diameter and 480 mm anchorage depth specimens.

Table 1
Mixture design of concrete.

Materials	Percentage by weight (%)
0–7 mm aggregate	30
7–15 mm aggregate	45
Cement	17
Water	8

When examining the anchors with a embedding depth of 120 mm, it was found that the lowest bearing strength of 27.9 kN when using adhesive type M10 and the highest capacity of 58.9 kN when using adhesive type M1. The average tensile capacity for anchors which had 120 mm depth and have been installed with 10 different types of adhesives was 45.5 kN. 5 materials have tensile strength value above this average value. When the failure modes were examined, concrete breakout was observed in 9 samples

Table 2
Properties of used chemical adhesives.

Material	Material structure	Number of component	Density (kg/l)	Compressive strength (MPa)
M1	Epoxy	Two	1.8	83
M2	Epoxy	Two	1.7	60
M3	Vinylester	Two	1.7	50
M4	Polyester	Two	1.7	74
M5	Epoxy	Two	1.45	104
M6	Polyester	Two	1.63	50
M7	Epoxy acrylic	Two	1.64	60
M8	Polyester	Two	1.60	55
M9	Epoxy Acrylic	Two	1.60	60
M10	Epoxy	Three	1.20	70

Fig. 2. Image for the tested samples.

and concrete breakout plus pull out was observed in 1 sample. When the anchors with 180 mm depth were examined, it was seen that the lowest capacity value was 42.6 kN when using adhesive type M10 while the highest capacity was 66.5 kN when using adhesive type M1. The average tensile capacity value of anchors with 180 mm depth and 10 different adhesives types was 58.4 kN. The tensile capacity values of 5 materials were below this average value. When the modes of failure were examined, 2 concrete breakout, 3 pull out and 5 concrete breakout plus pull out failure mechanisms were observed. For anchors with 240 mm depth, the lowest capacity was obtained for the adhesive type M3 with 47.9 kN and the highest capacity for the adhesive type M1 with 77.1 kN. The average tensile capacity of anchorages with 240 mm depth and 10 different adhesives was 63.4 kN. Only 4 materials were able to reach above this average tensile capacity value. When the modes of failure were examined, 4 concrete breakout, 4 pull out and 2 concrete breakout plus pull out failures were observed.

In general, anchors with a diameter of 12 mm were found to have the highest capacity values with adhesive type M1 and the lowest capacities with adhesive type M10. It has been found that as the depth increases, the tensile capacity increases too but when embedment depth was more than 15 with the using of adhesive materials types M3 and M9 that's led to decrease the capacities. Depending on the failure modes observed during the experimental work, it could be concluded that, the concrete breakout failure type is dominant for anchors installed at depths of 60 and 120 mm. also when the embedding depth increases, the pullout and concrete breakout failure mechanisms are affecting together.

3.1.2. 16 mm diameter anchors

For anchors with 16 mm diameter and 80 mm depth, the lowest tensile capacity obtained was 24.0 kN when using adhesive material type M9 and the highest capacity was 58.0 kN when using adhesive material type M5. The average tensile capacity for anchors with 80 mm depth and 10 different adhesive material types was 37.8 kN. 7 materials were below this average value. When the failure modes were examined, the concrete breakout failure type was observed in all samples. When the anchors with 160 mm embedment depth were examined, the lowest tensile capacity obtained was 31.7 kN when using adhesive material type M10 while the highest capacity obtained was 95.0 kN when using adhesive material type M5. The average tensile capacity of anchorages with 160 mm depth and 10 different adhesives was 71.0 kN. 4 materials have tensile strength above this average value. When examining the modes of failure, 7 samples showed concrete breakout failure while in 3 samples the concrete breakout and pull out failure mechanisms were observed together.

When examining the anchors with 240 mm embedment depth, the lowest tensile capacity obtained was 45.7 kN when using adhesive material type M10 and the highest capacity was 103.6 kN when using adhesive material type M1. The average tensile capacity for anchors with 240 mm depth and 10 different adhesive material types was 82.8 kN. The tensile capacities for 4 materials were below this average value. When examining the modes of failure, 7 samples showed concrete breakout failure, 1 pullout failure and 2 samples showed both concrete breakout and pull out failure mechanisms. In anchors with 320 mm embedment depth, the lowest tensile capacity obtained was 48.1 kN when using adhesive material type M10 while the highest capacity was 162.6 kN when using adhesive material type M1. The average tensile capacity for anchors with 320 mm depth and 10 different adhesive material types was 102.2 kN. Only 5 materials were able to achieve tensile strength above this average value. When examining the modes of failure, 6 samples showed concrete breakout failure, 2 pullout failure and 2 samples showed both concrete breakout and pull out failure mechanisms.

In general, anchors with a diameter of 16 mm have shown highest capacity values with adhesive material type M1 and the lowest capacities with adhesive material type M10. Also it was concluded that, as the embedment depth increases, the tensile capacity increases too but when embedment depth was more than 15Φ with the using of adhesive materials types M2, M6 and M9, the capacities decreased. Depending on the failure modes observed during the experimental work, it could be concluded that the concrete breakout failure type is dominant for anchors installed at depths of 80 mm and as the embedding depth increases, the pullout and concrete breakout failure mechanisms were affecting together.

3.1.3. 20 mm diameter anchors

For anchors with 20 mm diameter and 100 mm embedment depth, the lowest tensile capacity obtained was 19.0 kN when using adhesive material type M10 and the highest capacity was 95.2 kN when using adhesive material type M1. The average tensile capacity for anchors with 100 mm depth and 10 different adhesive material types was 50.9 kN. 4 materials were below this average value. Generally, the concrete breakout failure type was observed. Only in one sample the pullout failure was observed. When the anchors with 200 mm depth were examined, the lowest tensile capacity obtained was 27.7 kN when using adhesive material type M5 while the highest capacity obtained was 145.0 kN when using adhesive material type M1. The average tensile capacity of anchorages with 200 mm depth and 10 different adhesives was 101.5 kN. 5 materials have tensile strength above this average value. When examining the modes of failure, 5 samples showed concrete

Table 3
Experimental Parameters and Test Results.

Anchorage diameter (mm)	Anchorage depth (mm)	Adhesive types																			
		Tensile strength (kN)										Initial stiffness (kN/mm)									
		M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
12	5Φ	23.5	15.7	24.8	16.0	27.8	14.8	28.5	20.0	18.8	28.9	9.32	4.66	5.63	3.02	8.95	5.66	5.79	4.87	7.25	7.74
	10Φ	58.9	48.5	54.3	43.0	53.0	45.4	46.3	36.0	42.1	27.9	9.83	11.03	8.51	9.99	10.38	8.43	11.21	13.35	13.13	6.07
	15Φ	66.5	55.4	62.1	64.6	65.0	62.9	58.0	50.2	56.7	42.6	12.52	6.92	7.39	7.59	9.65	11.27	15.71	9.39	12.81	7.28
	20Φ	77.1	59.8	47.9	64.4	73.4	75.6	62.9	63.0	53.8	54.5	8.08	6.89	8.97	12.21	11.27	11.19	13.55	12.94	16.43	10.94
16	5Φ	49.3	33.2	36.4	37.1	58.0	28.1	41.2	32.0	24.0	38.9	13.12	8.90	6.92	9.56	13.41	6.89	–	7.12	8.69	10.73
	10Φ	87.3	63.7	82.6	82.6	95.0	68.3	67.7	63.9	67.2	31.7	11.37	6.30	8.89	10.20	10.86	17.35	10.51	16.06	5.80	8.05
	15Φ	103.6	93.1	78.6	88.4	101.5	74.8	88.2	82.7	71.5	45.7	10.95	10.96	14.15	9.16	13.64	12.54	12.15	12.12	7.48	9.16
	20Φ	162.6	85.0	121.0	97.9	123.1	73.7	137.2	110.8	62.8	48.1	16.73	12.30	12.26	13.77	13.46	10.52	15.00	15.06	5.69	15.71
20	5Φ	95.2	51.0	43.6	45.2	19.3	54.0	60.0	53.1	68.2	19.1	15.63	10.02	7.66	10.50	–	14.90	10.04	10.29	11.13	–
	10Φ	145.0	84.9	89.3	109.9	27.7	99.5	144.0	125.2	114.4	75.2	14.27	14.30	13.81	12.87	10.83	11.53	12.70	14.60	11.21	13.04
	15Φ	152.5	125.9	154.3	164.6	69.6	170.3	167.4	161.1	148.9	73.5	15.66	16.03	15.80	14.54	13.79	14.57	14.42	13.48	12.96	15.25
	20Φ	176.7	158.1	165.3	154.7	36.7	127.6	169.0	70.4	158.4	48.2	14.66	13.42	13.22	12.48	10.74	16.23	15.87	10.96	11.83	14.34
24	5Φ	117.5	90.2	95.5	85.7	102.9	79.4	33.0	36.9	35.3	73.5	7.64	15.74	11.92	18.20	14.60	11.51	8.42	7.54	5.73	16.91
	10Φ	253.5	165.8	209.9	171.0	110.8	178.6	71.1	127.0	122.9	130.7	15.84	12.70	18.00	23.14	17.92	12.81	9.36	15.30	13.54	17.04
	15Φ	282.8	242.0	260.7	219.5	230.4	237.9	216.6	227.1	234.7	254.0	22.15	14.63	19.46	11.28	12.71	14.95	13.26	14.71	17.98	10.01
	20Φ	267.8	215.0	207.8	269.6	284.8	269.7	229.3	283.7	279.3	248.0	16.63	15.62	17.80	14.96	12.16	15.12	12.25	17.82	16.87	12.58

Anchorage diameter (mm)	Anchorage depth (mm)	Adhesive types																			
		Displacement ductility ratio										Energy dissipation capacity (kN mm)									
		M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
12	5Φ	1.104	1.018	1.034	1.042	–	1.092	1.016	1.110	1.026	1.000	71.36	53.02	64.89	47.73	54.79	35.73	91.83	60.33	77.72	34.78
	10Φ	3.308	1.172	2.044	1.158	2.405	1.119	1.104	1.122	1.063	1.000	1012.00	422.75	662.57	507.16	611.66	465.76	311.01	311.86	184.34	30.87
	15Φ	5.047	2.039	1.008	1.006	3.516	2.613	1.172	1.032	2.362	1.009	1635.83	570.25	1331.54	1806.29	1277.61	1297.52	1231.97	268.30	609.29	111.68
	20Φ	4.330	1.185	1.457	1.003	3.577	2.319	2.619	1.376	1.089	1.041	1986.83	660.64	288.67	1301.13	1603.41	1754.10	1300.74	552.14	410.25	223.84
16	5Φ	1.093	1.034	1.616	1.717	1.057	1.097	–	1.087	1.311	1.154	214.85	204.91	96.58	313.50	223.29	105.34	91.47	208.95	99.04	82.41
	10Φ	1.299	1.272	1.242	1.468	1.033	1.021	1.453	2.200	1.038	1.079	790.03	687.21	682.75	1027.68	1592.72	945.11	781.07	467.86	666.61	41.89
	15Φ	1.040	1.006	1.341	1.514	2.291	1.157	1.557	1.114	1.099	1.000	1913.64	1555.48	956.72	1103.60	1765.64	554.47	1110.19	1033.69	799.28	50.72
	20Φ	8.255	1.069	3.020	1.754	2.618	1.274	1.865	1.379	1.145	1.112	2489.50	736.85	2154.08	2016.00	1728.77	813.42	1770.47	935.92	605.65	77.16
20	5Φ	1.055	1.104	1.297	1.034	–	1.001	1.631	1.057	1.117	–	299.20	243.40	229.09	84.81	69.91	121.52	231.62	166.27	293.23	28.74
	10Φ	2.125	5.543	1.469	3.125	1.204	2.539	1.429	1.814	2.727	1.050	2074.95	1520.44	1000.03	1753.24	189.36	1220.85	1390.00	1273.83	1331.51	231.91
	15Φ	4.829	1.227	1.863	1.899	1.616	1.863	2.062	1.511	1.747	1.099	2994.86	2405.09	2213.07	2322.12	551.65	3270.28	2899.65	1659.12	2829.18	158.82
	20Φ	3.102	1.691	1.810	1.694	4.441	1.964	2.319	1.022	1.750	1.089	3887.64	3305.87	2127.61	2791.46	161.38	1905.80	1937.55	960.89	1796.25	66.86
24	5Φ	1.017	1.178	1.108	1.496	1.040	1.034	1.101	1.532	1.088	1.062	812.34	432.96	858.76	577.50	457.69	299.53	300.22	224.40	96.55	180.21
	10Φ	1.804	1.717	1.209	3.049	1.093	1.624	2.608	1.457	2.381	1.110	4425.97	2197.42	2466.27	2879.35	542.30	2192.14	981.39	1351.16	1600.33	565.30
	15Φ	2.029	1.509	1.404	1.908	1.367	1.539	2.038	1.522	1.320	1.201	5023.29	5224.04	4541.85	4151.02	3366.66	3915.92	4009.52	3945.87	3424.70	4203.83
	20Φ	1.518	1.561	1.600	1.251	1.184	1.540	1.154	1.487	1.324	1.241	5051.50	3910.80	3168.67	4386.41	4817.56	4861.03	3176.51	4554.48	4779.40	4688.30

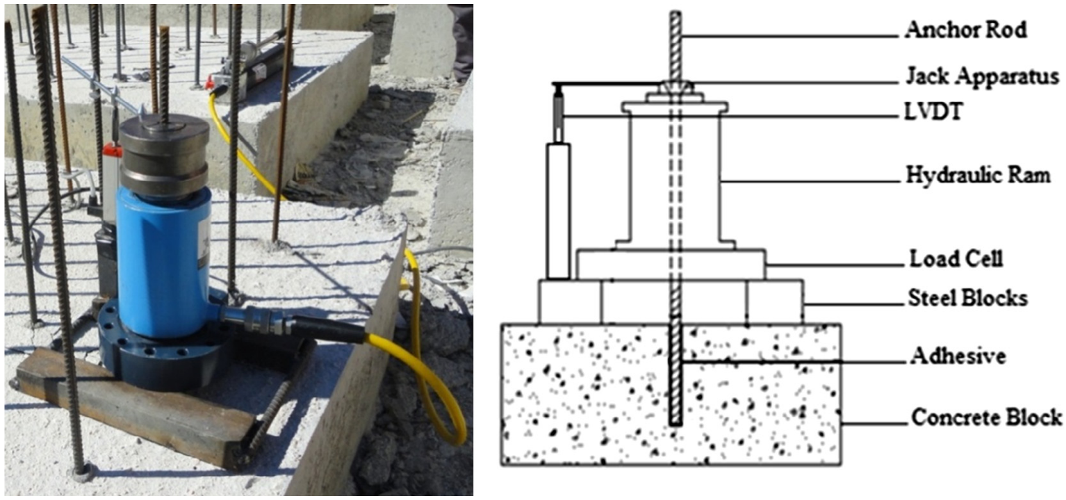


Fig. 3. Test setup.

breakout failure while in 4 samples the concrete breakout and pull out failure mechanisms were observed together.

When examining the anchors with 300 mm embedment depth, the lowest tensile capacity obtained was 69.6 kN when using adhesive material type M5 and the highest capacity was 167.4 kN when using adhesive material type M7. The average tensile capacity for anchors with 300 mm depth and 10 different adhesive material types was 138.8 kN. The tensile capacities for 3 materials were below this average value. When examining the modes of failure, 3 samples showed concrete breakout failure, 2 pullout failure and 5 samples showed both concrete breakout and pull out failure mechanisms. In anchors with 400 mm embedment depth, the lowest tensile capacity obtained was 36.7 kN when using adhesive material type M5 while the highest capacity was 176.7 kN when using adhesive material type M1. The average tensile capacity for anchors with 400 mm depth and 10 different adhesive material types was 126.5 kN. 7 materials were able to achieve tensile strength above this average value. When examining the modes of failure, 2 samples showed concrete breakout failure, 4 pullout failure and 4 samples showed both concrete breakout and pull out failure mechanisms.

In general, anchors with a diameter of 20 mm had shown highest capacity values with adhesive material type M1 and the lowest capacities with adhesive material type M10. Also it has been found that as the embedment depth increases, the tensile capacity increases too but when embedment depth was more than 15Φ with the using of adhesive materials types M4, M5, M6, M8 and M10, the tensile capacities decreased. Depending on the failure modes observed during the experimental work, it could be seen that the concrete breakout failure type and the pullout plus concrete breakout failure mechanisms were affective.

3.1.4. 24 mm diameter anchors

For anchors with 24 mm diameter and 120 mm embedment depth, the lowest tensile capacity obtained was 33.0 kN when using adhesive material type M7 and the highest capacity was 117.5 kN when using adhesive material type M1. The average tensile capacity for anchors with 120 mm depth and 10 different adhesive material types was 75 kN. 4 materials were below this average value. Generally, the concrete breakout failure type was observed. Only in one sample the pullout failure was observed. When the anchors with 240 mm depth were examined, the lowest tensile capacity obtained was 71.1 kN when using adhesive material type M7 while the highest capacity obtained was 253.5 kN when using adhesive material type M1. The average tensile capacity of anchorages with 240 mm depth and 10 different adhesives was 154.1 kN. 5 materials have tensile strength above this average value. When examining the modes of failure, 5 samples showed concrete breakout failure while in 4 samples the concrete breakout and pull out failure mechanisms were observed together. In anchors with 360 mm embedment depth, the lowest tensile capacity obtained was 216.6 kN when using adhesive material type M7 while the highest capacity was 282.75 kN when using adhesive material type M1. The average tensile capacity for anchors with 360 mm depth and 10 different adhesive material types was 240.6 kN. 6 materials were below this average value. When examining the modes of failure, 5 samples showed pull out failure and 5 samples showed concrete breakout plus pull out failure mechanisms. In anchors with 480 mm embedment depth, the lowest tensile capacity obtained was 229.3 kN when using adhesive material type M7 while the highest capacity was 284.8 kN when using adhesive material type M5. The average tensile capacity for anchors with 480 mm depth and 10 different adhesive material types was 255.5 kN. 6 materials were able to achieve tensile strength above this average value. When examining the modes of failure, 4 samples showed pull out failure and 6 samples showed concrete breakout plus pull out failure mechanisms.

In general, when examining the anchors with a diameter of 24 mm, the highest capacity values was obtained when using adhesive material type M1 and the lowest capacities was obtained when using adhesive material type M7. Also, it has been found that as the embedment depth increases, the tensile capacity increases too but when embedment depth was more than 15Φ with the using of adhesive materials types M1, M2, M3 and M10, the tensile capacities decreased. Depending on the failure modes observed during the experimental work, it could be seen that the concrete breakout failure type and the pullout plus concrete breakout failure mechanisms were affective.

In this study 10 different types of adhesives were used to install the anchorages. From these materials, M10 was a mixture of three components which was prepared by the manufacturer. All other products were of two component and ready-mixed products in the cartridge. M1, M2, M5 and M10 are epoxy based, M4, M6 and M8 are polyester based, M7 and M9 are epoxy acrylic based and M3 is vinyl based chemical adhesive. When all of the samples were examined, it was seen that the highest tensile capacities were obtained for anchors installed by using epoxy-based material M1 and the lowest capacities when using epoxy-based material M10.

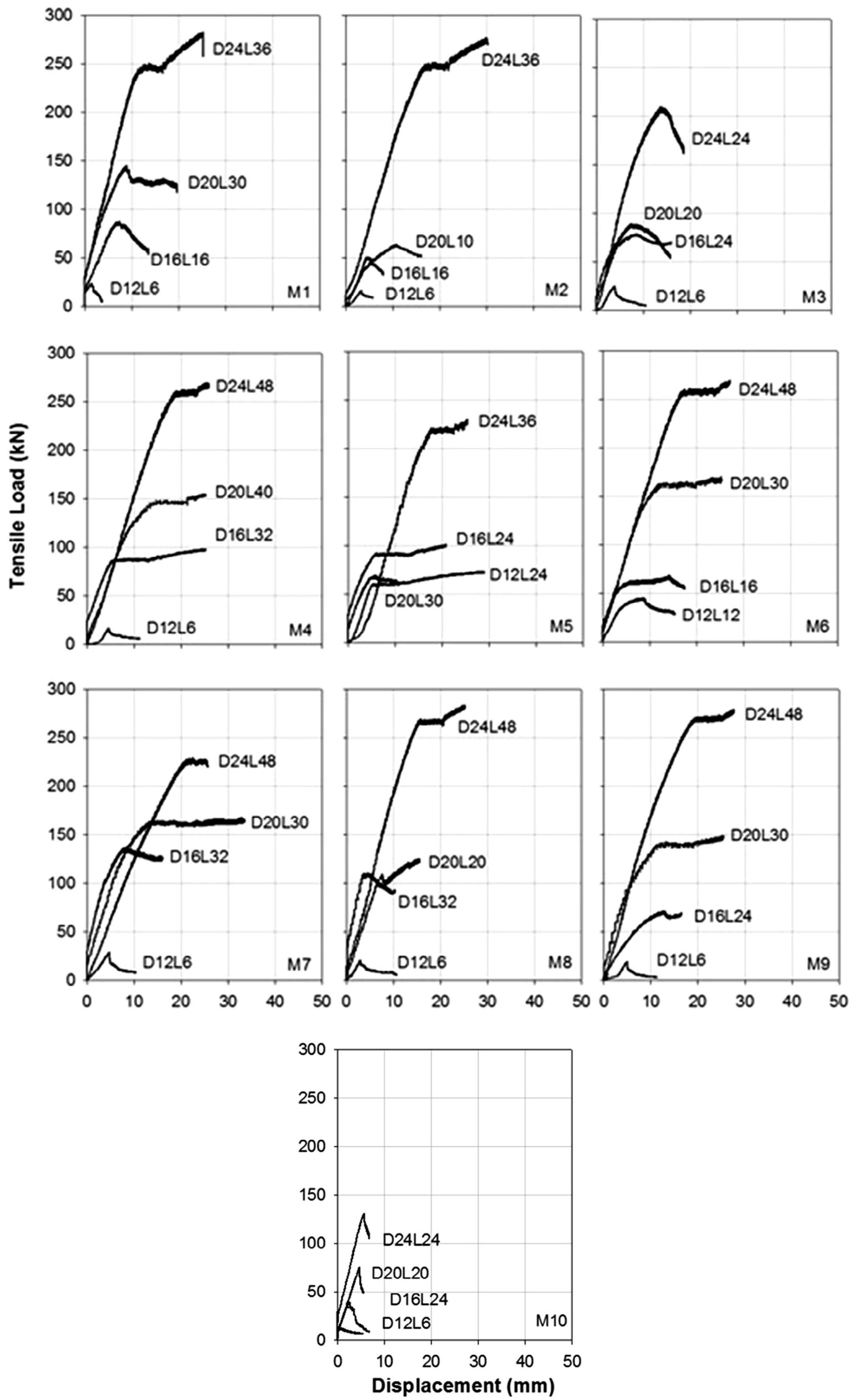


Fig. 4. Load-displacement relationships for some of the tested specimens.

Fig. 5. Failure mechanism for some of the tested specimens.

3.2. Strength and initial stiffness

As a result, for the tensile tests, the tensile strength values obtained with 10 different adhesive types are shown in Fig. 6 and the adherence strength values are given in Fig. 7. Generally, it was shown that as the diameter increases, the tensile capacity will increase. The tensile strength and initial stiffness values for 160 samples which were tested in this study are given in Table 3. When a general evaluation is made, the initial stiffness values showed reduction after increasing the embedding depth over 10Φ.

In the tested specimens with 12 mm diameter, the increasing of the embedding depth from 5Φ to 10Φ led to increase the rate of axial pulling capacity from 25% to 55%, except for adhesive type M10 which showed a reduction in the axial pulling capacity. The usage of chemical adhesive M3, M4 and M9 led to a reduction in the axial pulling capacity for embedment depth over 15Φ.

In the tested specimens with 16 mm diameter, the increasing of the embedding depth from 5Φ to 10Φ led to increase the axial pulling capacity from 15% to 45%, except for adhesive type M10 which showed a reduction in the axial pulling capacity. In the elements with chemical adhesive type M1, increasing the embedding depth of anchors led to a clear increase in the axial pulling capacity. The usage of chemical adhesive M2, M6 and M9 led to a reduction in the axial pulling capacity for anchors with embedment depth more than 15Φ. In the group of this sample, the M6, M9 and M10 chemical adhesives which are based on polyester, acrylic and a three

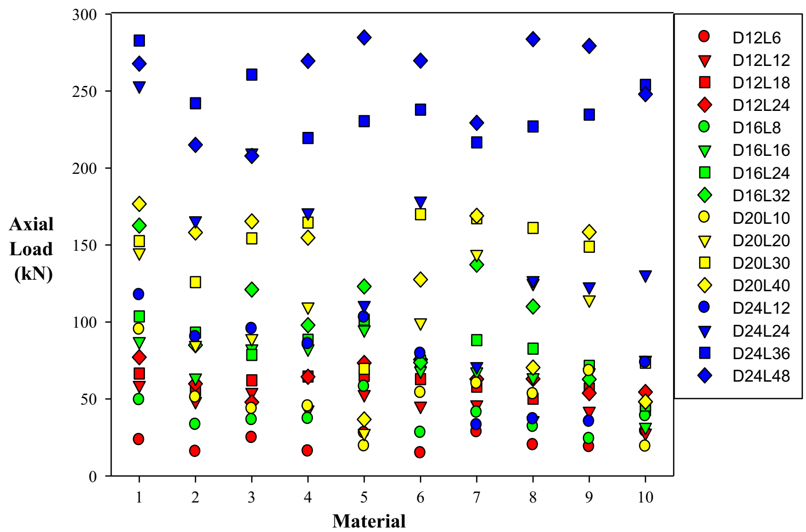


Fig. 6. Tensile strengths according to chemical adhesive type.

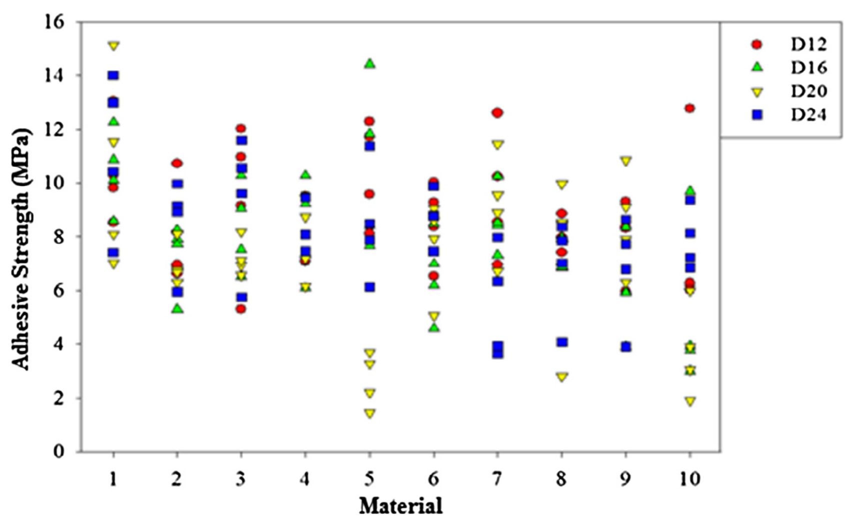


Fig. 7. Adherence strengths according to chemical adhesive type.

component epoxy generally exhibited lower capacity than other materials.

Test specimens with 20 mm diameter showed a significant increase in the axial pulling capacity when the depth of embedding increased from 5Φ to 10Φ. In test specimens with 5Φ embedding length, the axial pulling capacity observed to be close to each other for all adhesives types except for adhesive types M5 and M10. The usage of the chemical adhesives M5 and M10 exhibited lower tensile capacity in test specimens with 20 mm diameter.

In test specimens with 24 mm diameter and embedding length of 5Φ, It was observed that the tensile capacity of the anchors was low .and When the depth of anchorage increases from 5φ to 10φ, the axial tensile capacities increase from 20% to 90% while the axial tensile capacity decreases when using adhesive types M1, M2, M3 and M10 with embedment length of 20Φ.

3.3. Displacement ductility ratio

Ductility ratios were determined by using the load-displacement curve taking into account the failure types. The displacement ductility ratios for the tested elements were calculated by the ratio of failure point displacement values to yield point displacement values. In the tested elements, the failure point is considered to be the point at which the value of the maximum tensile capacity is reduced from 15% to 85%, and the displacement at this point is considered as the failure point displacement. The yielding point is considered to be the point of maximum carrying force in the test elements and the displacement at this point was used as the yielding point displacement. The values of ductility rates for all samples are given in Table 3. When the ductility rate was evaluated according to the materials types, it was obvious that, the highest values were observed when using adhesive material type M1 and the lowest values were observed when using adhesive material type M10. Generally, as the embedment length increases to 15Φ the ductility ratios will be increased and it will be decreased after 15Φ. Also increasing the anchor diameter up to 20 mm leads to increasing the ductility ratio and whereas increasing anchor diameter more than 20 mm causes reduction of the ductility ratio.

3.4. Energy dissipation capacity

The energy dissipation capacities were calculated for each tested element. The energy dissipation capacities were calculated from the load-displacement curves obtained during the test. Energy dissipation capacities were determined by calculating the area under load-displacement curves up to the point of collapse. The energy dissipation capacity values for all samples are given in Table 3. As diameters and embedding depth increase, the energy dissipation capacities values increases too. The highest value for energy dissipation capacities appear when using adhesive type and the lowest value in adhesive type M10.

The average energy dissipation capacities for the tested elements which had 12 mm diameter and 60 mm embedding length were 59.2 kN-mm. 5 types of adhesives (M1, M3, M7, M8, and M9) have exceeded this value. The value of average energy dissipation capacities for elements with 12 mm diameter and 120 mm embedding length was 452 kN-mm. 5 types of adhesives (M1, M3, M4, M5, and M6) have exceeded this value. for the elements with 12 mm diameter and 180 mm embedding length, the average energy dissipation capacities was 1014 kN-mm. 6 types of adhesives (M1, M3, M4, M5, M6 and M7) had average energy dissipation capacities above this value. The average energy dissipation capacities for the tested elements which had 12 mm diameter and 240 mm embedding length were 1008 kN-mm. 5 types of adhesives (M1, M4, M5, M6 and M7) have exceeded this value.

The average energy dissipation capacities for the tested elements which had 16 mm diameter and 80 mm embedding length was 164 kN mm. 5 types of adhesives (M1, M2, M4, M5 and M8) have exceeded this value. The value of average energy dissipation capacities for elements with 16 mm diameter and 160 mm embedding length was 768 kN-mm. 4 types of adhesives (M4, M5, M6 and M7) have exceeded this value. for the elements with 16 mm diameter and 240 mm embedding length, the average energy dissipation capacities was 1084 kN-mm. 5 types of adhesives (M1, M2, M4, M5 and M7) had average energy dissipation capacities above this value. While the average energy dissipation capacities for the tested elements which had 16 mm diameter and 320 mm embedding length was 1333 kN-mm. 5 types of adhesives (M1, M3, M4, M5 and M7) have exceeded this value.

The average energy dissipation capacities for the tested elements which had 20 mm diameter and 100 mm embedding length was 177 kN-mm. 5 types of adhesives (M1, M2, M3, M7 and M9) have exceeded this value. The value of average energy dissipation capacities for elements with 20 mm diameter and 200 mm embedding length was 1198 kN-mm. 7 types of adhesives (M1, M2, M4, M6, M7, M8 and M9) have exceeded this value. For the elements with 20 mm diameter and 300 mm embedding length, the average energy dissipation capacities were 2130 kN-mm. 7 types of adhesives (M1, M2, M3, M4, M6, M7 and M9) had average energy dissipation capacities above this value. While the average energy dissipation capacities for the tested elements which had 20 mm diameter and 400 mm embedding length was 1894 kN-mm. 7 types of adhesives (M1, M2, M3, M4, M6, M7 and M9) have exceeded this value.

The average energy dissipation capacities for the tested elements which had 24 mm diameter and 120 mm embedding length were 424 kN-mm. 5 types of adhesives (M1, M2, M3, M4 and M5) have exceeded this value. The value of average energy dissipation capacities for elements with 24 mm diameter and 240 mm embedding length was 1920 kN-mm. 5 types of adhesives (M1, M2, M3, M4 and M6) have exceeded this value. For the elements with 24 mm diameter and 360 mm embedding length, the average energy dissipation capacities were 4180 kN-mm. 4 types of adhesives (M1, M2, M3 and M10) had average energy dissipation capacities above this value. While the average energy dissipation capacities for the tested elements which had 24 mm diameter and 480 mm embedding length was 4340 kN-mm. 7 types of adhesives (M1, M4, M5, M6, M8, M9 and M10) have exceeded this value.

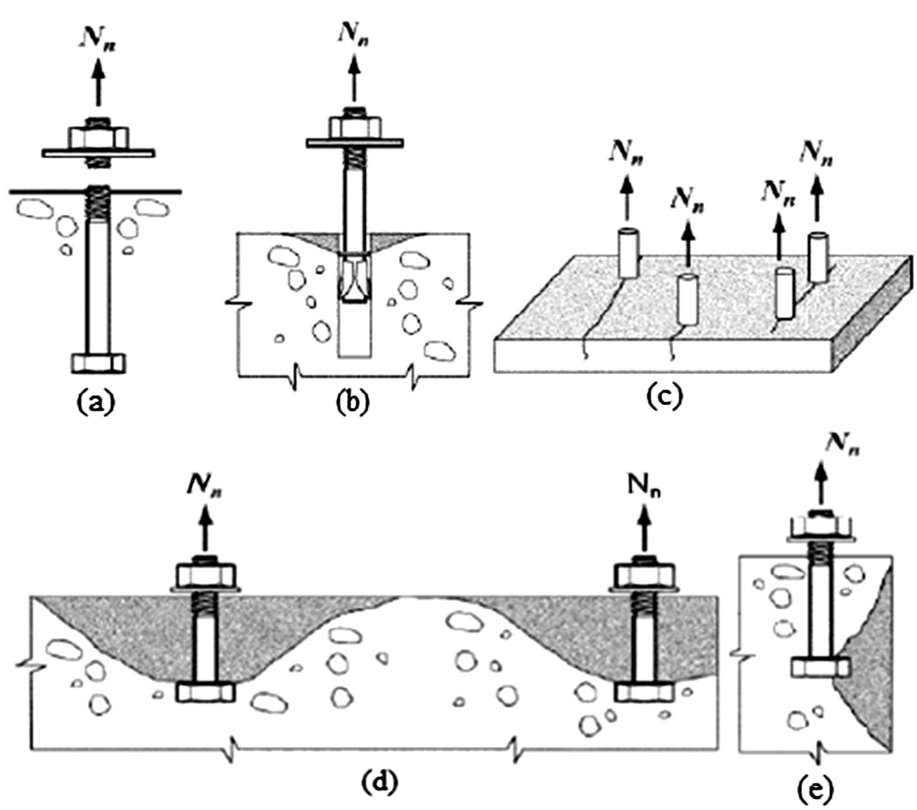


Fig. 8. Anchorage failure mechanisms, (a) Steel Failure (b) Pullout (c) Concrete Splitting (d) Concrete Breakout, (e) Side-face Blowout.

4. Analytically study

The American Concrete Institute (ACI 318 Appendix-D) has separated the setting of anchors to concrete into two main groups: anchors setting during casting of concrete, and anchors setting to hardened concrete. The mechanisms of failure of chemical anchors steed to hardened concrete under the influence of axial tensile force are; conical separation of concrete, formation of conical separating and peeling together, pull out of anchors, cutting of anchors and splitting of concrete (Fig. 8). Analytical bearing strength values and modes of failure for the test elements were calculated by using the formula specified in ACI 318 Appendix-D and given in Table 4. After calculating the axial tensile capacities, the designed resistances capacities were determined according to the theoretical failure modes. Anchorage strength reduction factor; according to ACI 318 Appendix-D, was determined depending on the failure shapes of the damaged reinforcement and concrete. In case of damaged of reinforcement; 0.75 for ductile steel, for concrete cone damage; unreinforced, C1 (slightly affected by workmanship and environmental conditions, high reliability) 0.65. The safety levels were determined by proportioning the experimental test results to the capacity and design strengths (Fig. 9).

Considering the strength capacities, the number of samples with a safety level above 1, was exceeded 50% when using adhesive type M1, 44% for adhesive type M3, for adhesive types M4, M5, M6 and M7 was between 30 and 40%, for adhesive types M2 and M8 was 25% and finally for adhesive types M9 and M10 was below 20%.

When examining the failure modes according to ACI 318, generally the concrete breakout failure were observed when the embedding depth was less than 15Φ while the steel failure mode was observed for embedment depth greater than 15Φ. When comparing these results with the experimental results, there was a compatibility of 79% in failure modes.

Experimental capacities were scaled relative to code values (calculated as per ACI 318 Appendix D) to more accurately calculate the experimental capacities. The coefficients used for the scaling are plotted in Fig. 11. In this figure, test specimens are grouped and 4 graphics are plotted each consisting of 4 different anchorage embedment depth. Trend lines are used to obtain the equations that may provide the scale factors, for the values calculated as per ACI 318, which can be used to scale the analytical values. By the used of proposed scaling equations scale factors compatible with experimental results may be obtained. From the inspection of equations, it was observed that the R^2 values calculated for the equations proposed for anchorages with diameters of 12 mm and 16 mm and 5Φ embedment depth were very low and using them may not be suitable. Same conclusions are valid for the equations proposed for

Table 4
Estimated values according to ACI 318 and test results.

Anchorage diameter (mm)	Embedment depth (mm)	ACI 318		Tensile strength (kN)/experimental failure mode				
		Tensile strength (kN)	Failure Mode	M1	M2	M3	M4	M5
12	5Φ	18.26	Concrete breakout	23.5/CB	15.7/CB	24.8/CB	16.0/CB	27.8/CB
	10Φ	51.65	Concrete breakout	58.9/CB	48.5/CB	54.3/CB	43.0/CB+P	53.0/CB
	15Φ	71.59	Concrete breakout	66.5/CB+P	55.4/P	62.1/CB+P	64.6/CB+P	65.0/CB+P
	20Φ	71.59	Steel Failure	77.1/CB	59.8/CB+P	47.9/CB	64.4/P	73.4/CB+P
16	5Φ	28.11	Concrete breakout	49.3/CB	33.2/CB	36.4/CB	37.1/CB	58.0/CB
	10Φ	79.52	Concrete breakout	87.3/CB	63.7/CB	82.6/CB	82.6/CB	95.0/CB+P
	15Φ	133.36	Steel Failure	103.6/CB+P	93.1/CB	78.6/CB	88.4/CB	101.5/CB+P
	20Φ	133.36	Steel Failure	162.6/CB	85.0/CB	121.0/P	97.9/P	123.1/CB+P
20	5Φ	39.29	Concrete breakout	95.2/CB	51.0/CB	43.6/CB	45.2/CB	19.3/P
	10Φ	111.14	Concrete breakout	145.0/CB	84.9/CB+P	89.3/CB	109.9/CB	27.7/P
	15Φ	204.17	Concrete breakout	152.5/CB+P	125.9/CB	154.3/CB+P	164.6/CB+P	69.6/P
	20Φ	208.38	Steel Failure	176.7/CB+P	158.1/CB+P	165.3/P	154.7/CB+P	36.7/P
24	5Φ	51.65	Concrete breakout	117.5/CB	90.2/CB	95.5/CB	85.7/CB	102.9/P
	10Φ	146.09	Concrete breakout	253.5/P	165.8/CB	209.9/CB	171.0/CB+P	110.8/CB+P
	15Φ	268.39	Concrete breakout	282.8/P	242.0/P	260.7/P	219.5/CB+P	230.4/P
	20Φ	300.06	Steel Failure	267.8/P	215.0/CB+P	207.8/P	269.6/CB+P	284.8/CB+P

Anchorage diameter (mm)	Embedment depth (mm)	ACI 318		Tensile strength (kN)/experimental failure mode				
		Tensile strength (kN)	Failure mode	M6	M7	M8	M9	M10
12	5Φ	18.26	Concrete breakout	14.8/CB	28.5/CB	20.0/CB	18.8/CB	28.9/CB
	10Φ	51.65	Concrete breakout	45.4/CB	46.3/CB	36.0/CB	42.1/CB	27.9/CB
	15Φ	71.59	Concrete breakout	62.9/P	58.0/P	50.2/CB	56.7/CB+P	42.6/CB
	20Φ	71.59	Steel Failure	75.6/P	62.9/P	63.0/P	53.8/CB	54.5/CB
16	5Φ	28.11	Concrete breakout	28.1/CB	41.2/CB	32.0/CB	24.0/CB	38.9/CB
	10Φ	79.52	Concrete breakout	68.3/CB	67.7/CB	63.9/CB+P	67.2/CB+P	31.7/CB
	15Φ	133.36	Steel Failure	74.8/CB	88.2/CB	82.7/CB	71.5/P	45.7/CB
	20Φ	133.36	Steel Failure	73.7/CB	137.2/CB	110.8/CB	62.8/CB+P	48.1/CB
20	5Φ	39.29	Concrete breakout	54.0/CB+P	60.0/CB	53.1/CB	68.2/CB	19.1/CB
	10Φ	111.14	Concrete breakout	99.5/CB+P	144.0/CB+P	125.2/CB+P	114.4/CB	75.2/CB
	15Φ	204.17	Concrete breakout	170.3/CB+P	167.4/CB	161.1/P	148.9/CB+P	73.5/CB
	20Φ	208.38	Steel Failure	127.6/CB	169.0/P	70.4/P	158.4/CB+P	48.2/CB
24	5Φ	51.65	Concrete breakout	79.4/CB	33.0/CB	36.9/CB	35.3/CB	73.5/CB
	10Φ	146.09	Concrete breakout	178.6/CB+P	71.1/CB	127.0/CB+P	122.9/CB	130.7/CB
	15Φ	268.39	Concrete breakout	237.9/CB+P	216.6/CB+P	227.1/CB+P	234.7/CB+P	254.0/P
	20Φ	300.06	Steel Failure	269.7/P	229.3/CB+P	283.7/CB+P	279.3/CB+P	248.0/P

CB: Concrete breakout, P: Pull-out.

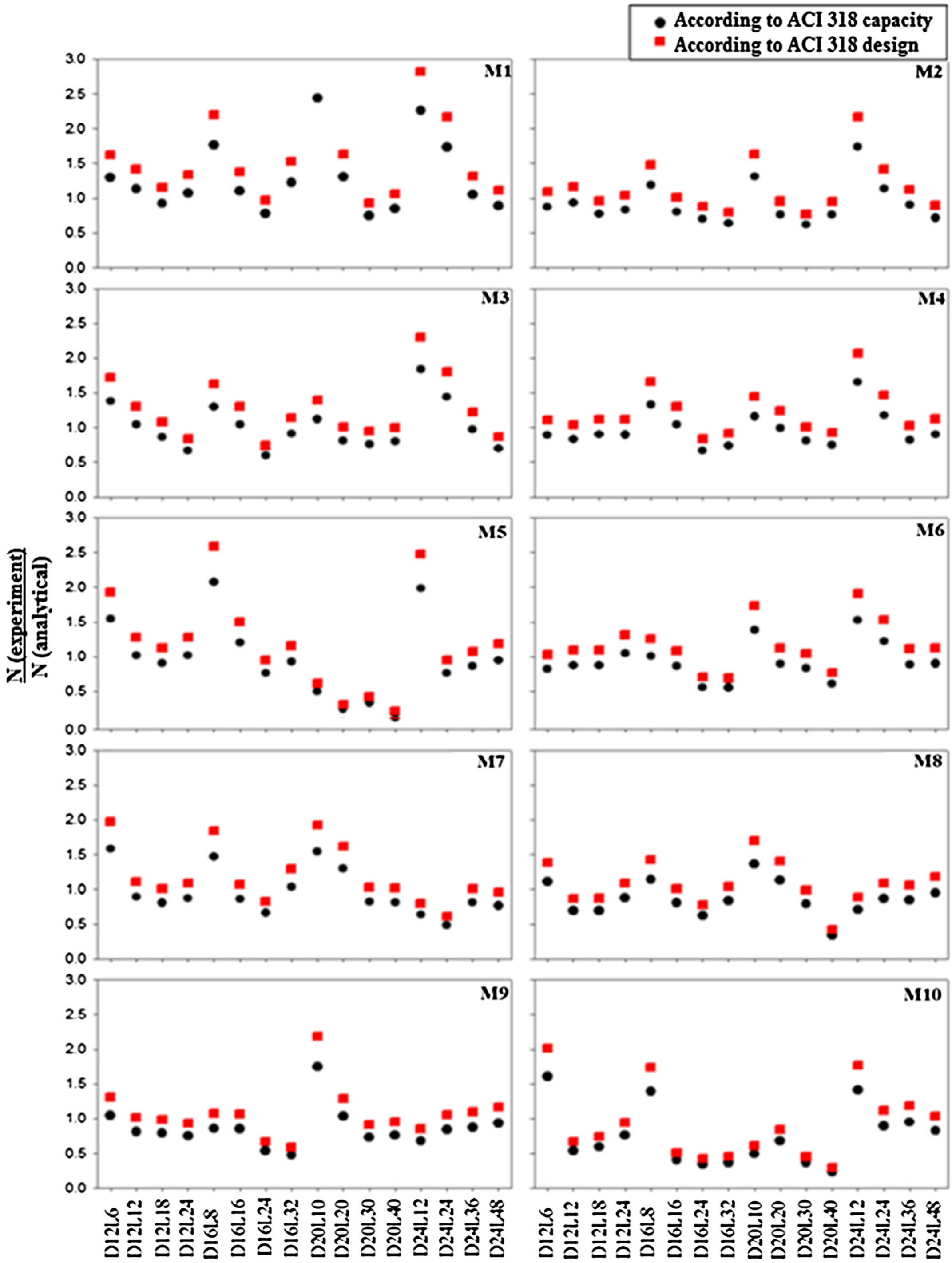


Fig. 9. Safety levels according to the chemical adhesive type.

anchorages with 20 mm diameter and 15Φ and 20Φ embedment depths. For the other equations R^2 values are acceptable.

5. Conclusions

The addition of new structural elements to the existing reinforced concrete structure is frequently conducted by using the chemical anchorage method. More than one type of adhesive is used in the chemical anchorage applications. Each of the chemical adhesive used has different mechanical properties under standard conditions. Once again, this study has demonstrated the importance of adhesive type effect on the axial tensile force capacity of the anchor. 3 different brands of adhesive material which are frequently used in the market (polyester, vinylester, epoxy and epoxy acrylic based products) were used in this study.

It has been observed that the using of adhesive type M1 in the tested elements led to a fully interlock, which in turn led to exceed the yield strength of the anchorage and that caused anchorage-welded failure. in contrast to this, when using adhesive type M10, the adhesive or concrete cone breakage failure mechanisms

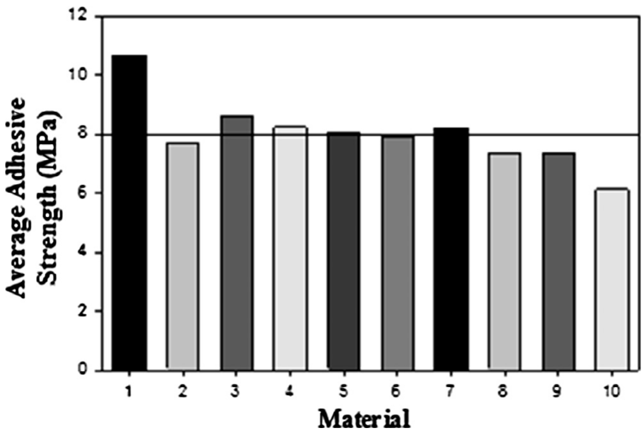


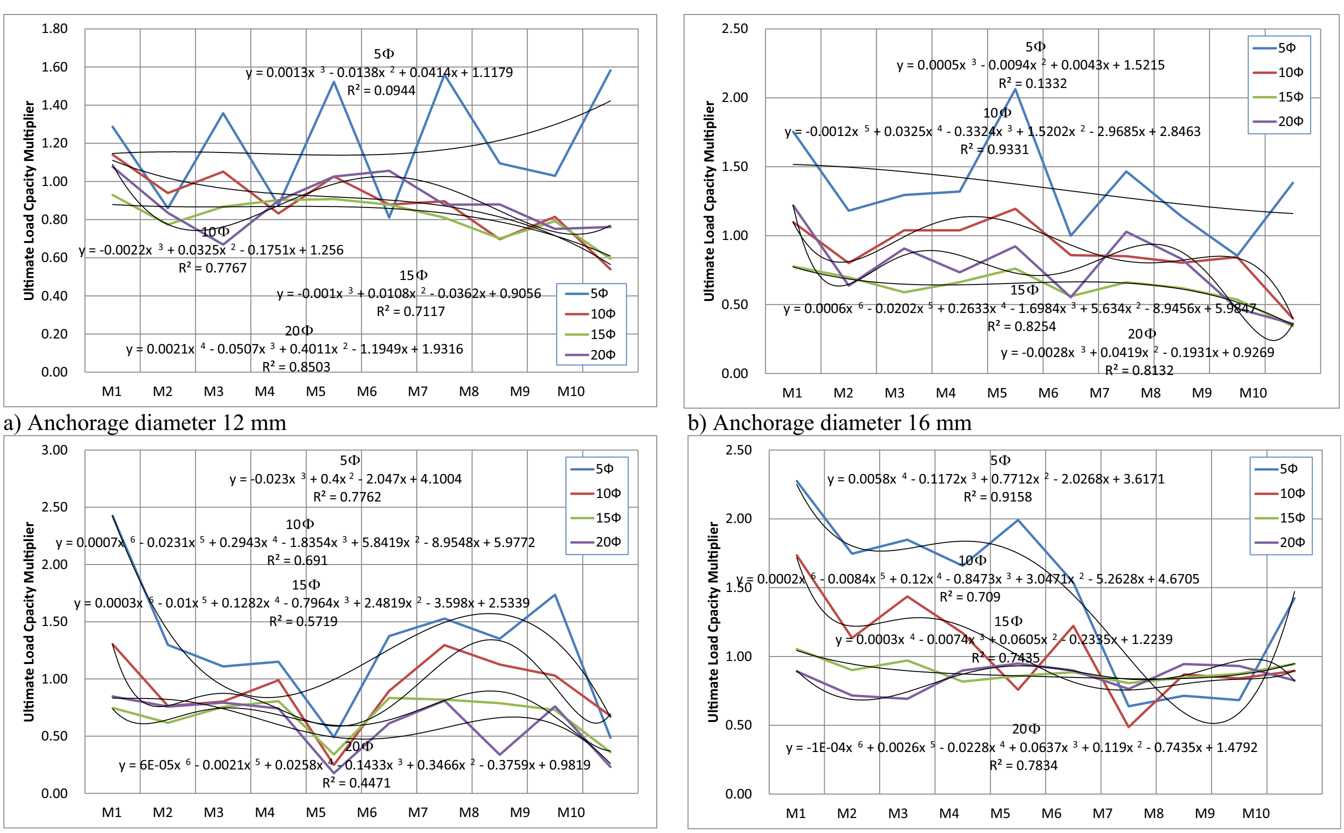
Fig. 10. Average adherence stresses according to material type.

were observed without reaching the yield strength of the anchorage. It has been found that the usage of chemical adhesive type M10 which containing 3 components lead to difficulty in application and negatively reflected on the interlock. In chemical adhesives, many types of filler are added especially for the epoxy to enhance strength, viscosity, thermal expansion coefficient and electricality. In the test program, the additive material for the three-component chemical adhesive was quartz sand.

In general and according to the axial tensile capacity for the chemical anchors, the increasing of the anchorage diameter leads to increase the axial tensile strength. The elements which didn't show an increase in strength with increasing the embankment depth were; in the elements of 12 mm diameter anchors with vinlyester and acrylic, in the elements of 16 mm diameter anchors withe epoxy, polyester and acrylic, in the elements of 20 mm diameter anchors polyester and epoxy and in the elements of 24 mm diameter anchors with epoxy and vinlyester based adhesives respectively and embedding depth of 20Φ.

In the study, it was observed that using an embedment depth of 10Φ or 15Φ (dependent to anchor diameter) is enough to provide full tensile capacity. In shallow (<5Φ) and very deep (>20Φ) anchors, the increase in strength wasn't continuously observed. The effect of chemical adhesive type was clear in specimens with large diameter (>20 mm) and embedding depths of 10Φ and 15Φ. Under these conditions, the samples in which epoxy-based chemicals were used showed the highest strength.

The safety levels which are given in Fig. 9 were obtained when the capacities and design strengths proposed by ACI 318 Appendix-D are compared to experimental axial tensile capacities. when the experimental axial load capacities were compared to the design capacity proposed by ACI 318 Appendix-D, the tested elements with chemical adhesives M1, M2 and M3 found to be 95% safe. In the method of ACI 318 there is no parameter dependent to the type of chemical bond agent. However, the experiments revealed that the mechanical properties of the chemical agent are effective on the strength. Generally, the adherence strengths for the used chemical adhesives were between 5 and 12 MPa. The best adhesive strength results were achieved when using adhesive type M1 and the worst strength when using adhesive type M10. The average adhesive stresses of the chemical adhesives used were found to be between 6 and 11 MPa (Fig. 10). The average adherence stress for the 10 chemical adhesives used in the experiment was 8 MPa. Between the 10 different products which were selected from the frequently used materials in the market, only 5 groups could reach for this average value.



a) Anchorage diameter 12 mm
b) Anchorage diameter 16 mm
c) Anchorage diameter 20 mm
d) Anchorage diameter 24 mm

Fig. 11. Ultimate load capacity multiplier for ACI 318 capacity values.

The best behavior for axial tensile capacity in the test program was obtained when using two-component epoxy adhesives while the worst behavior was shown when using three-component epoxy-based chemical adhesive. The effect of the used chemical adhesive type was clear in large anchor diameters (>20 mm). While, the effect of chemical adhesive type was not significant in anchors with shallow depth such as 5Φ and 10Φ. The effect of the chemical adhesive on the anchorage strength was evident when the depth of embedment over 10Φ. According to the results obtained from the test program, it was found that the ideal embedding depth for anchors with 16 mm diameter was 10Φ while in anchors with 20 and 24 mm diameter the ideal embedding depth was 15Φ. This study has shown that the mechanical properties of the chemical adhesive are extremely important.

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