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Aggregate Type and Concrete Age Effects on Anchor Breakout Performance: Large Database and Insights

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Abstract: This contribution summarizes the largest available literature data collection on tensile and shear loaded anchor tests, obtained in two independent studies and performed by two different research groups. It was the objective of the two studies to investigate a possible effect that petrographically different coarse aggregate types may have on the tensile and shear load capacity for concrete breakout failure modes. In total, seven normal-strength and four high-strength concretes were tested at two different ages. Structural tests were performed on cast-in (tensile and shear tests) and post-installed adhesive anchors (shear tests). Parallel to the structural tests, each concrete was characterized in terms of compressive and tensile strength. Finally, the combined experimental data offer novel insights into the predictive quality of available design models for concrete cone capacity in tension and edge breakout in shear with respect to a potential aggregate effect. Systematic analyses indicate only minor aggregate effects after normalization by compressive strength (less than 7% difference between normalized values). However, the study reveals potential curing and concrete age effects where a 9% increase in predicted values is shown when concrete cures longer. The predictive equations remain conservative in comparison to all the investigated properties and their validity is shown in this study.

Keywords: concrete; fasteners; aggregate effect; aging; cone capacity; edge breakout; photogrammetry



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1. Introduction

Nowadays, fastening systems have become an essential part of the construction process. Characterized by a relatively easy installation process, fasteners have contributed to everyday use in different areas of application [1–3]. The safe and reliable use of fasteners is ensured by rigorous testing as part of an approval/qualification process that fasteners must undergo. The required tests are based on the current state-of-the-art and design models and are deemed to cover all critical scenarios. However, the qualification guidelines give a noticeable and necessary amount of freedom related to concrete composition, age, and curing to laboratories, which can cause differences in experimentally obtained load capacities.

Typically, fasteners are placed (cast-in, post-installed) in a base material, often concrete, and are used to transfer applied loads to the structure. Concrete, as one of the most widely used construction materials, has been intensively studied worldwide by the research community. A wide range of possible concrete properties is the result of different mix designs and locally available raw materials. These properties constantly change due to the complex aging nature dependent on the long-lasting hydration of cement [4,5] and its dependence on the thermal history. Past [6] and current design codes and qualifications [7–10] provide limited information concerning the influence of the coarse aggregate type used in concrete. It is suggested only to use aggregates of medium hardness. Over the years, numerous

studies have been performed investigating the effect of mix design and raw materials on concrete mechanical properties [11–16] (e.g., effect of aggregate type on compressive strength). However, there is a lack of such studies on the behavior of fasteners. Therefore, in this study we aim to investigate the influence of coarse aggregate petrography and, in a limited sense, curing state on anchor load capacities.

In design, concrete is typically characterized by means of compressive strength only [8,17,18], and most design equations are directly formulated in terms of compressive strength. If other material properties, such as, e.g., Young's modulus, are required, they are predicted from compressive strength by means of empirical models. This implies that compressive strength is generally sufficient as the sole tested material property to capture the influence of mix design and concrete composition on the actually governing mechanical properties within their typical range. Similarly, compressive strength is the only material mechanical property required to predict the resistance of an anchor related to concrete failure modes (e.g., concrete cone capacity, concrete edge breakout, etc.) [19], regardless of the concrete class, cement, or aggregate type or the fact that it is a fracture mechanics problem [20–24]. Therefore, it is assumed that there is no additional effect on anchor load performance beyond what is implicitly considered by compressive strength.

Additionally, it is important to note that current qualification guidelines [9,10] specify only a minimum concrete age at the time of testing—21 days—but do not explicitly specify maximum age. Curing and storage conditions are quite loosely defined even though they affect the evolution of hydration degree and, in turn, concrete mechanical properties. As long as the concrete compressive strength obtained at the same age complies with the strength class, no further effect is expected. The only given maximum age concerns tests for bond properties of post-installed adhesive anchors, where the age of the concrete member should not exceed 18 months [25] unless comparison tests with concrete aged less than 3 months are conducted. Regional variations in concrete properties and a so-called aggregate effect on bond properties are addressed by inter-laboratory round-robin tests. Recent studies by Ninčević et al. [26,27] documented a pronounced aging effect on concrete cone capacity in tension and edge breakout in shear between 28 and 70 days, even after normalization with the respective concrete compressive strength.

Research Significance

Current anchor design codes and anchor qualification guidelines provide quite limited guidance related to concrete mix design, curing, and storage as well as the age of testing. Regarding the coarse aggregate used, merely medium hardness is specified, leaving the range of possibly resulting concrete properties wide open. The only determined material property that enters design equations and qualification rules is concrete compressive strength. This contribution summarizes the largest data set ever created of an aggregate effect on anchor capacity, obtained in two independent studies and performed by two different research groups. The combined experimental data are analyzed and novel insights into the predictive quality of available design models for concrete cone capacity in tension and edge breakout in shear with respect to a potential aggregate effect as well as age effect are presented.

2. Materials and Methods

2.1. Overview

This contribution summarizes the results of two independent experimental campaigns performed by two research groups: (i) Christian Doppler Laboratory (later labeled “CDL”), University of Natural Resources and Life Sciences, Vienna, Austria, and (ii) Centre Scientifique et Technique du Bâtiment, France (later “CSTB”). Each group performed a set of experiments comprising aggregate and concrete characterization tests and structural tests on anchors under tensile and shear loading in accordance with the unconfined tension test setup [10] and edge breakout shear test setup [7,10]. The slabs were cast in accordance with the uncracked concrete test member provisions [7,10]. The slabs were not reinforced in the unconfined test regions to avoid the influence of reinforcement on the behavior of the

anchor (unrestricted breakout area). The slabs contained reinforcement to allow handling and the distribution of load transmitted by the test equipment. CDL performed both concrete material characterization and structural tests at 28- and 70-day concrete age, while CSTB performed tests at 28 and 180 days. In total, the presented results cover 11 different concretes and include 78 cube compression tests, 100 anchor pull-out tests, and 87 anchor shear tests. All slabs for anchor tests and specimens for material characterization belonging to a specific concrete were cast from the same concrete batch.

2.1.1. Choice of Coarse Aggregates

Three different coarse aggregate types were used for the CDL tests. The aggregate types were chosen based on the geological region as a representative aggregate used in the Central European concrete industry. Based on the performed mineralogical powder XRD analysis, aggregates can be grouped as quartz, limestone, and basalt aggregates. CSTB used four different aggregates, where three of them originated from France (named based on the region as Blanquefort, Prasville, and La Brosse) and one originated from Canada (named Orca). Based on the petrography, these aggregates belong to different groups: Blanquefort—alluvial silicate, Prasville—limestone, La Brosse—alluvial, and Orca—volcanic and igneous rock. Apart from petrographic differences, for some concretes, aggregate shape and maximum aggregate size varied. A detailed summary of aggregate properties is provided in Tables 1–3.

Table 1. Differences in mix design among CDL concrete batches.

Mix Design/Batch	CDL 1	CDL 2	CDL 3
Cement content (kg/m ³)	274.9	274.8	289.5
Aggregate/cement ratio	7.19	7.49	7.36
Water/cement ratio	0.63	0.60	0.58
Aggregate type	Agg. 1 Quartz	Agg. 2 Limestone	Agg. 3 Basalt
Aggregate shape	Round	Round	Broken
Max aggregate size—mm (in.)	16 (0.63)	16 (0.63)	22 (0.87)

Table 2. Differences in mix design among CSTB low-strength concrete batches.

Mix Design/Batch	CSTB 1a	CSTB 2a	CSTB 3a	CSTB 4a
Cement content (kg/m ³)	320	330	320	288
Aggregate/cement ratio	5.5	5.3	5.5	6.1
Water/cement ratio	0.56	0.59	0.68	0.59
Aggregate type	Agg. 4 Blanquefort Alluvial Silicate	Agg. 5 Prasville Limestone	Agg. 6 La Brosse Alluvial	Agg. 7 Orca Magmatic Rock
Aggregate shape	rolled	crushed	semi-crushed	semi-crushed
Max aggregate size—mm (in.)	20 (0.79)	20 (0.79)	20 (0.79)	14 (0.55)

Table 3. Differences in mix design among CSTB high-strength concrete batches.

Mix Design/Batch	CSTB 1b	CSTB 2b	CSTB 3b	CSTB 4b
Cement content (kg/m ³)	420	420	435	420
Aggregate/cement ratio	4.3	4.3	4.2	4.3
Water/cement ratio	0.41	0.42	0.48	0.46
Aggregate type	Agg. 4	Agg. 5	Agg. 6	Agg. 7
Aggregate shape	rolled	crushed	semi-crushed	semi-crushed
Max aggregate size—mm (in.)	20 (0.79)	20 (0.79)	20 (0.79)	14 (0.55)

2.1.2. Determination of Mix Design

Two approaches were considered for the mix design: (i) CDL cast three different low-strength concretes (named CDL 1–3) mainly differing in the aggregate type used, while all the other parameters were kept virtually constant as much as possible. Obviously, this approach leads to different concrete compressive strengths. All CDL concretes used the same cement type, CEM II 42.5N; (ii) CSTB, on the other side, aimed to have four low-strength concretes with cement type CEM II/B-LL 32.5R (named as CSTB 1a–4a) and four high-strength concretes with CEM I 52.5N cement (named as CSTB 1b–4b). Each concrete of each strength class used different aggregate types. This approach aimed for a largely constant concrete compressive strength within each strength class and required a preliminary experimental campaign in which CSTB optimized the mix designs. The grading curve for all cast concretes respects EOTA Technical Report 48 requirements [9]. Table 1 summarizes the exact mix design for all three concretes cast by the CDL team.

As can be seen from Table 1, all three CDL concretes have almost the same aggregate-to-cement and water-to-cement ratios. The main difference is the petrography and the granulometric distribution of the coarse aggregate. It has to be noted that it was not possible to obtain a maximum aggregate size of 16 mm (0.63 in.) for concrete CDL 3, and therefore a maximum aggregate size of 22 mm (0.87 in.) was used.

The mix design parameters for all other concretes cast and tested by CSTB are shown in Tables 2 and 3 for low-strength and high-strength concretes, respectively. For both CSTB concrete classes it can be clearly seen that the mix design parameters significantly differ among concretes of one class. It is well known that petrography, size, and shape of aggregates are important factors influencing concrete mechanical properties [11–15]. Consequently, it is not surprising that for concretes with different aggregates, different mix design parameters are required in order to achieve the same compressive strength.

2.1.3. Choice of Fasteners

CDL performed structural tensile tests on cast-in headed studs, while shear tests were carried out using bonded anchors. CSTB used cast-in headed studs for both structural tests in tension and shear. In the case of tensile tests, both groups used the same anchor type, M20 hex-bolt screws with welded-on washers, as shown in Figure 1a, with an embedment depth (h_{ef}) of 100 mm (3.94 in.).

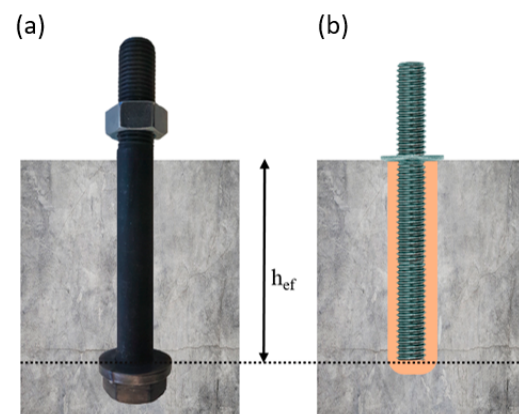


Figure 1. Mechanical (a) and bonded (b) anchor system considered in this investigation.

In the case of shear tests, CDL used a bonded anchor system made of post-installed M16 threaded bar with a vinyl-ester-based adhesive, while CSTB used the same headed stud anchor type as for tension. Figure 1b shows the sketch of the bonded anchor system used for the CDL shear tests. All shear tests were performed for all concretes and ages for one edge distance (c_1) and one embedment depth (h_{ef}) of 100 mm (3.94 in.). Table 4 summarizes the content of this study and the differences between both experimental campaigns.

Table 4. Summary of experimental campaigns.

Item/Group	CDL	CSTB
Number of concretes: low strength	3	4
Number of concretes: high strength	-	4
Number of different aggregates	Agg. 1–3	Agg. 4–7
Tests performed at (days):	28 and 70	28 and 180
Tension tests	Headed studs	Headed studs
Shear tests	Bonded anchors	Headed studs

2.1.4. Slab Geometries

The CDL anchor tests under tensile loading were performed in slabs with dimensions of $250 \times 100 \times 30 \text{ cm}^3$ ($8.20 \times 3.28 \times 0.98 \text{ in.}^3$). For each concrete age, four unconfined tension tests were executed, requiring in total six slabs for 24 tests. CSTB used three different slab sizes: (i) $290 \times 120 \times 25 \text{ cm}^3$ ($11.41 \times 4.72 \times 0.98 \text{ in.}^3$), (ii) $290 \times 130 \times 25 \text{ cm}^3$ ($11.41 \times 5.12 \times 0.98 \text{ in.}^3$), and (iii) $130 \times 130 \times 25 \text{ cm}^3$ ($5.12 \times 5.12 \times 0.98 \text{ in.}^3$). For each concrete age, 5 unconfined tension tests were performed, resulting in a total of 80 unconfined tension tests and 28 required concrete slabs.

2.1.5. Loading Conditions

As mentioned before, two anchor loading scenarios were considered: (i) tensile loading and (ii) shear loading. Structural tests with tensile loading were performed in a so-called “unconfined configuration”, typically triggering concrete cone breakout failure. The undisturbed development of a concrete cone with respect to the peak load requires a distance between anchor and closest support of no less than $1.5 \times h_{ef}$. In this case, the concrete slab was supported by a steel ring with an inner diameter of 400 mm (15.75 in.), equal to $4 \times h_{ef}$. Anchor shear tests were performed by loading anchors perpendicular to a free edge by means of a steel sword resting on the concrete surface. The distance between steel supports parallel to the edge was six times the edge distance ($6c_1 = 600 \text{ mm} = 23.62 \text{ in.}$), ensuring negligible effects of the supports on the peak load. Significant friction between the steel sword and concrete were avoided by Teflon sheets.

For both test types, the anchors were installed in a layout limiting the influence of adjacent anchors (overlapping cones) or free edges. All structural tests were performed under quasistatic (tensile or shear) loading in displacement-control at constant rate with a time to peak ranging from 1–3 min [9]. The load was applied by hydraulic jacks in setups with spherical couplings that minimize bending moments. The displacement sensor used for the closed-loop control system was a linear variable differential transformer (LVDT) measuring the difference between the anchor close to the concrete surface and the steel ring in the case of CDL [26] and on top of the anchor in the case of the CSTB test setup.

2.1.6. Concrete Age Influence

Typically, most of the concrete-related experimental investigations are executed at concrete aged approximately 28 days. Twenty-eight-day concrete material properties, mostly the concrete compressive strength (f_c), are the standard input parameters for structural design. As a result, both groups performed their first tests at 28 days. In general, design codes and fastening approval documents provide only minimum requirements for concrete age (see earlier discussion), and specific rules concerning the ambient moisture and temperature conditions during curing and storage are missing completely. This is rather problematic as the temperature and humidity history determine the development of hydration and other chemical reactions, which in turn cause the development of mechanical properties such as compressive strength, tensile strength, and Young’s modulus. The different mechanical properties develop at different rates as described by the evolution models of ACI [28] and fib [18]. Depending on the investigated problem, this may alter

the prediction of failure loads or even trigger different failure mechanisms. Appreciating the complex aging nature of concrete is an important factor, especially when tests from different laboratories/countries are compared, even if they are supposedly executed at the same age. Ultimately, the concrete age is an arbitrary number and largely depends on the history of ambient temperature and humidity conditions. What should be defined is the actual concrete maturity level or a combination of age and storage conditions. Recently, a comprehensive experimental analysis performed by Ninčević et al. [26] demonstrated an age and cure dependence of the concrete cone breakout capacity and suggested that the age effect in some cases might be more dominant than other mix and composition effects.

3. Results

3.1. Material Characterization

In this section, the experimentally obtained material properties for all different aggregates and concretes will be presented. Selected coarse aggregates were mechanically characterized by means of standard Los Angeles (L.A.) tests, identifying the coefficient of abrasion in accordance with EN 1097-2 [29]. For each concrete, standard compression tests were performed in parallel to the anchor tests at both ages, yielding compressive strength (f_c) estimates. For most concretes, Brazilian splitting tests were performed as well to identify the corresponding tensile strength (f_t) values.

3.1.1. Coarse Aggregate Properties

In order to mechanically characterize each type of coarse aggregate, standard L.A. abrasion tests were carried out [29]. This well-established test is commonly used in the paving (e.g., roads) industry to indicate the aggregate quality and to evaluate a coefficient of abrasive resistance. Figure 2 shows results for all different aggregates used in this study, where blue circles represent aggregates used by CDL, and red circles represent aggregates of CSTB.

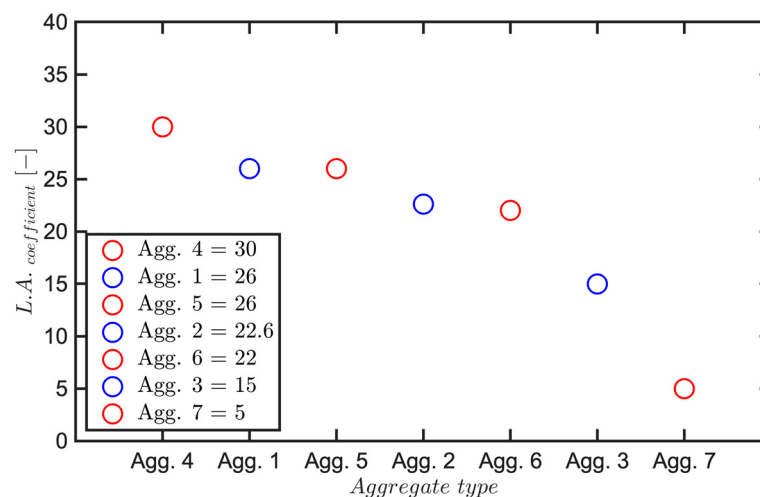


Figure 2. Los Angeles (L.A.) coefficients for the chosen coarse aggregates.

Figure 2 shows the wide range of L.A. coefficients covered in this study, including the most practically relevant aggregates in the concrete-fastening industry.

3.1.2. Concrete Mechanical Properties

Standard concrete compressive strength tests [30] were carried out in order to identify the mechanical properties of each investigated concrete. Compressive strength ($f_{c,150}$) values were obtained on cubes with a side length of 150 mm (5.91 in.) in parallel with the anchor tests. The cubes and concrete slabs used for anchor tests underwent the same curing and storage conditions, satisfying anchor approval guidelines [9], until tested. Figure 3 summarizes all experimentally obtained concrete compressive strengths (f_c) plotted against

the corresponding L.A. coefficient. Each color represents a research group and marker style concrete-strength class: blue circles for CDL, red circles for CSTB normal-strength concrete, and red diamond markers for CSTB high-strength concrete. Additionally, empty markers represent 28-day test results, while filled markers represent results for the second age (70 days for CDL tests and 180 days for CSTB tests).

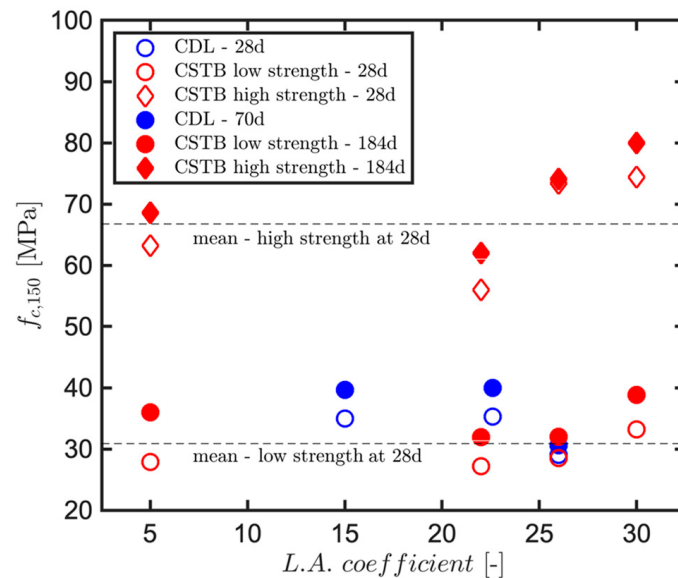


Figure 3. Concrete cube compressive strength ($f_{c,150}$) for all tested concretes and ages (note: 1 MPa = 0.15 ksi).

As shown in Figure 3, the covered concrete compressive strengths (f_c) are widely spread among concretes, with a minimum of 27.2 MPa (3.9 ksi) at 28 days and a maximum of 80 MPa (11.6 ksi) at the 184-day age. It is shown that the L.A. coefficient is not or barely correlated with the compressive strength since for substantially different L.A. coefficients, almost the same compressive strength can be found (e.g., empty and/or filled circles). Compressive strength characterization tests show that CDL and CSTB low-strength concretes (blue and red empty circles) finally belong to the same concrete class with mean compressive strength of ~31 MPa (~4.5 ksi) at 28 days. As expected, the high-strength concretes (empty diamonds) show a significantly higher compressive strength with a mean value of ~67 MPa (~9.7 ksi). The mean compressive strength values and respective coefficients of variation for all concretes and ages are listed in Table 5, together with the experimentally obtained indirect tensile strength (f_t) values from Brazilian splitting tests. Each mean value is based on five tests for CDL and three tests for CSTB.

For both anchor failure mechanisms considered in this investigation—concrete cone failure and edge breakout—the concrete compressive strength (f_c) is the only material parameter involved in anchor load capacity predictions according to ACI [28,31] and fib [18]. Thus, the discussion is limited to this material property. More insights into correlations between concrete cone capacity and other concrete properties as well as aggregate properties and concrete properties are given in Ninčević et al. [32] for the CDL concretes in which other concrete mechanical properties, including cylinder compressive strength, compressive loading modulus, and total fracture energy, are reported.

Table 5. Experimentally obtained concrete cube compressive strength.

Class	Batch/ Agg. Type	$f_{c,150}$ at 1st Age MPa (ksi)	f_t at 1st Age MPa (ksi)	$f_{c,150}$ at 2nd Age MPa (ksi)	f_t at 2nd Age MPa (ksi)
low strength	CSTB 1a/Agg. 4	33.2 (4.8) $\pm$ 3.3%	2.6 (0.4) $\pm$ 8.2%	38.8 (5.6) $\pm$ 4.0%	2.7 (0.4) $\pm$ 7.0%
	CDL 1/Agg. 1	29.1 (4.2) $\pm$ 5.0%	3.0 (0.4) $\pm$ 20.8%	30.6 (4.4) $\pm$ 5.5%	3.4 (0.5) $\pm$ 8.6%
	CSTB 2a/Agg. 5	28.5 (4.1) $\pm$ 6.4%	2.5 (0.4) $\pm$ 4.3%	32.0 (4.6) $\pm$ 4.3%	2.7 (0.4) $\pm$ 2.2%
	CDL 2/Agg. 2	35.3 (5.1) $\pm$ 3.4%	4.1 (0.6) $\pm$ 3.3%	40.0 (5.8) $\pm$ 6.7%	4.4 (0.6) $\pm$ 4.2%
	CSTB 3a/Agg. 6	27.2 (3.9) $\pm$ 1.1%	2.3 (0.3) $\pm$ 9.7%	31.9 (4.6) $\pm$ 6.3%	-
	CDL 3/Agg. 3	35.0 (5.1) $\pm$ 6.3%	3.4 (0.5) $\pm$ 2.0%	39.7 (5.8) $\pm$ 8.0%	3.5 (0.5) $\pm$ 9.1%
	CSTB 4a/Agg. 7	27.9 (4.0) $\pm$ 5.3%	2.0 (0.3) $\pm$ 5.0%	36.0 (5.2) $\pm$ 13.1%	-
High strength	CSTB 1b/Agg. 4	74.4 (10.8) $\pm$ 1.2%	4.3 (0.6) $\pm$ 4.8%	80.0 (11.6) $\pm$ 2.6%	4.5 (0.7) $\pm$ 1.7%
	CSTB 2b/Agg. 5	73.4 (10.6) $\pm$ 2.8%	3.5 (0.5) $\pm$ 4.6%	74.1 (10.7) $\pm$ 2.1%	4.3 (0.6) $\pm$ 11.9%
	CSTB 3b/Agg. 6	56.0 (8.1) $\pm$ 1.1%	-	62.0 (9.0) $\pm$ 1.3%	-
	CSTB 4b/Agg. 7	63.2 (9.1) $\pm$ 1.0%	4.1 (0.6) $\pm$ 6.2%	68.6 (9.9) $\pm$ 2.9%	-

3.2. Anchor Results

In the following chapter, first the experimental data obtained from anchor tests in tension and shear are summarized.

3.2.1. Tensile Loading—Summary of Experimentally Determined Concrete Cone Capacities

An overview of the experimentally determined concrete cone capacities is shown in Figure 4, where the tensile load capacity is plotted against the L.A. coefficient of the aggregate used. The color code and marker code are consistent with the previously presented Figure 3 and subsequent figures. Each plotted marker in Figure 4 represents the mean value of four tests for CDL and five tests for CSTB.

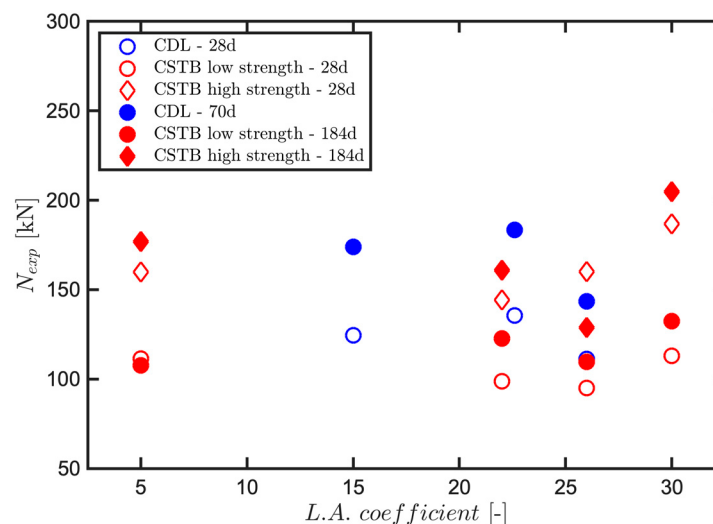


Figure 4. Experimentally obtained concrete cone capacities for all tested concretes and ages (note: 1 kN = 0.225 kip).

The plotted data clearly demonstrate that the L.A. coefficient is not a suitable parameter to evaluate the influence of aggregate type on concrete cone capacity [32]. For substantially different L.A. coefficients, almost similar concrete cone capacities can be obtained within one concrete class. The same lack of a trend was previously found in the case of concrete compressive strengths. Table 6 summarizes the mean concrete cone capacities and respective COVs of all investigated concretes and ages.

Table 6. Experimentally obtained concrete cone capacities.

Class	Batch/Agg. Type	N_{exp} at 1st Age kN (kip)	N_{exp} at 2nd Age kN (kip)
low strength	CSTB 1a/Agg. 4	113.0 (25.4) $\pm$ 14.7%	132.3 (29.7) $\pm$ 8.6%
	CDL 1/Agg. 1	111.2 (25.0) $\pm$ 8.3%	143.4 (32.2) $\pm$ 4.9%
	CSTB 2a/Agg. 5	95.0 (21.4) $\pm$ 11.0%	109.6 (24.6) $\pm$ 12.1%
	CDL 2/Agg. 2	135.6 (30.5) $\pm$ 9.6%	183.4 (41.2) $\pm$ 7.0%
	CSTB 3a/Agg. 6	98.9 (22.2) $\pm$ 7.3%	122.7 (27.6) $\pm$ 6.9%
	CDL 3/Agg. 3	124.4 (28.0) $\pm$ 1.2%	173.8 (39.1) $\pm$ 5.6%
	CSTB 4a/Agg. 7	111.4 (25.0) $\pm$ 11.0%	107.7 (24.2) $\pm$ 14.5%
High strength	CSTB 1b/Agg. 4	186.8 (42.0) $\pm$ 10.3%	204.8 (46.0) $\pm$ 11.4%
	CSTB 2b/Agg. 5	160.0 (35.9) $\pm$ 13.1%	128.8 (29.0) $\pm$ 3.5%
	CSTB 3b/Agg. 6	144.3 (32.4) $\pm$ 5.2%	160.9 (36.2) $\pm$ 13.1%
	CSTB 4b/Agg. 7	159.8 (35.9) $\pm$ 15.9%	176.9 (39.8) $\pm$ 12.1%

3.2.2. Shear Loading—Summary of Experimentally Determined Edge Breakout Capacities

Anchor shear tests were performed on the same concrete slabs used for unconfined tension tests. For each slab, first anchor shear tests were performed in order to minimize damage of the concrete member, preventing potential splitting cracks of the member due to the tensile tests and its effect on shear load capacity. Anchor for the shear tests were spaced sufficiently (fulfilling code requirements) to prevent interactions. Experimentally obtained shear load capacities for all concretes and ages are shown in Figure 5, where each marker represents the mean of four tests for CDL concretes and five tests for CSTB concretes. For some CSTB concretes, only the first age was tested due to logistical reasons. Table 7 summarizes all experimentally obtained mean shear capacities plotted in Figure 5, including their respective coefficients of variation.

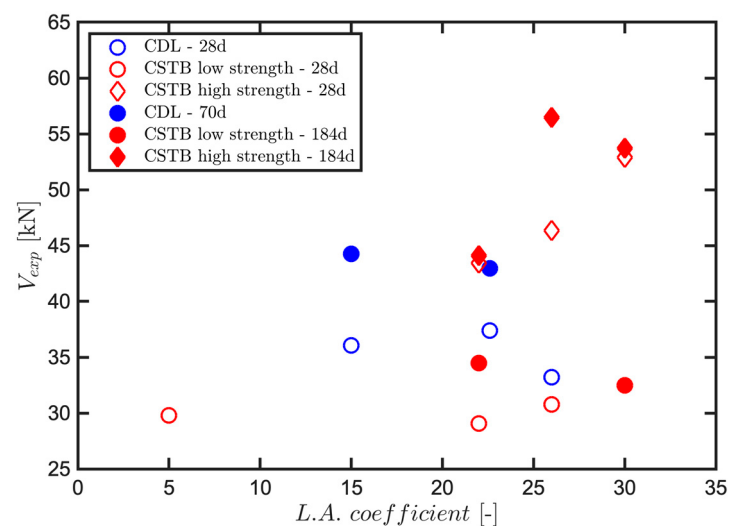


Figure 5. Experimentally obtained edge breakout capacities for all tested concretes and ages (note: 1 kN = 0.225 kip).

Table 7. Experimentally obtained concrete edge breakout capacities.

Class	Batch/Agg. Type	V_{exp} at 1st Age kN (kip)	V_{exp} at 2nd Age kN (kip)
low strength	CSTB 1a/Agg. 4	32.5 (7.3) $\pm$ 6.8%	32.5 (7.3) $\pm$ 6.1%
	CDL 1/Agg. 1	33.2 (7.5) $\pm$ 1.5%	-
	CSTB 2a/Agg. 5	30.8 (6.9) $\pm$ 6.5%	-
	CDL 2/Agg. 2	37.4 (8.4) $\pm$ 9.0%	42.9 (9.6) $\pm$ 4.6%
	CSTB 3a/Agg. 6	29.1 (6.7) $\pm$ 9.9%	34.5 (7.8) $\pm$ 11.9%
	CDL 3/Agg. 3	36.1 (8.1) $\pm$ 4.7%	44.3 (10.0) $\pm$ 2.3%
	CSTB 4a/Agg. 7	29.9 (4.0) $\pm$ 14.5%	-
High strength	CSTB 1b/Agg. 4	52.9 (11.9) $\pm$ 17.8%	53.7 (12.1) $\pm$ 3.9%
	CSTB 2b/Agg. 5	46.3 (10.4) $\pm$ 10.5%	56.5 (12.7) $\pm$ 14.7%
	CSTB 3b/Agg. 6	43.4 (9.8) $\pm$ 9.2%	44.1 (9.9) $\pm$ 15.3%
	CSTB 4b/Agg. 7	61.5 (13.8) $\pm$ 10.4%	-

In line with the results of the tensile tests, the analysis of the shear tests also reveals the absence of any correlation between shear capacity and L.A. coefficient. As expected, high-strength concretes (red diamond markers) result in the highest ultimate loads.

4. Discussion

The presented analysis is solely based on design models in terms of compressive strength (f_c). Naturally, an aggregate effect on anchor failure loads is found since all mechanical properties are affected by mix design and choice of coarse aggregate. Thus, the discussion focuses on the question whether the compressive strength can fully explain the observed differences between different concretes and different ages. To that end, the anchor load capacities are normalized using the design models by removing the known functional dependencies, in particular those on compressive strength. Finally, the comparison of normalized anchor capacities isolates additional effects (such as e.g., aggregate or age effects) that are not accounted for in the model.

4.1. Anchor Results under Tensile Loading

4.1.1. Empirical Equation for Concrete Cone Breakout Capacity

Current anchor design according to ACI 318 [28] or EN1992-4 [33] is based on an empirical prediction model as given by Equation (1) to calculate the concrete cone capacity. This approach is known as concrete capacity design (CCD) in the US and was first introduced as concrete capacity method (CC method) by Fuchs et al. [19].

$$N_{CCD} = k \cdot h_{ef}^{1.5} \cdot \sqrt{f_c} \quad (1)$$

According to Equation (1), the concrete cone capacity N_{CCD} [N] depends on a product-dependent calibration factor k with dimensional units [$\text{N}^{0.5}/\text{mm}^{0.5}$], the anchor embedment depth h_{ef} [mm], and the concrete compressive strength f_c [MPa]. Calibration factor k depends on the anchor type (e.g., cast-in or post-installed anchors) and differences in codes exist owing to the choice of unit system (SI or USCS). In the case of cast-in headed studs, $k = 15.5$ (SI units) is recommended in combination with a concrete strength [MPa] measured on cubes with a size of 200 mm (7.78 in.). If USCS units are used with concrete compressive strength [psi] measured on 6×12 in. cylinders, $k = 40$ ($\text{lb}^{0.5}/\text{in}^{0.5}$).

It has to be noted that compressive strength is used in the CCD method out of convenience only since it is the material property available in design. The actual failure mechanism is determined by fracture mechanics and depends on tensile strength, Young's modulus, and fracture energy. This is also the reason for the dependence on $h_{ef}^{1.5}$, the

strongest possible size effect according to linear elastic fracture mechanics (LEFM). The square root of compressive strength is only an empirical approximation for the actually relevant material parameters and was calibrated on tests typically performed at 28 days. The actual behavior may, thus, deviate from this approximation for other ages or specific concrete mixes, e.g., as a function of coarse aggregate type. Further deviations can be expected, e.g., dependent on the head size [34] or specific anchor geometry.

4.1.2. Aggregate Effect at Given Age

A simple approach to detect systematic errors in an empirical model, such as an aggregate effect, is the comparison with an experimental data set that covers a large range of different realizations of the parameter in question (here, coarse aggregate type, L.A. coefficient). The ratio between measurement N_{exp} and predicted concrete cone capacity N_{CCD} is a straightforward quantitative measure of prediction quality and is often calculated as relative prediction error.

The inverse of the relative prediction error can be interpreted as normalized measurement values in which the known functional dependence on important input parameters is removed. In this case, the relative concrete cone capacity in tension is defined by Equation (2):

$$v_t(t) = \frac{N_{exp}(t)}{N_{CCD}(t)} = \frac{N_{exp}(t)}{k \cdot h_{ef}^{1.5} \cdot \sqrt{f_c(t)}} \quad (2)$$

and can be calculated for all mixes and ages. Ideally, v_t is equal or close to 1.0 for all tested concrete mixes and ages. A systematic deviation from 1.0 would indicate that the empirical model is (i) not properly calibrated for the specific anchor type (k factor) or (ii) does not account for an essential influence factor. The latter case can be detected by a large variability in relative concrete cone capacities. Naturally, the results have to be interpreted with respect to the typical experimental scatter caused by imperfections in the setup and material uncertainties, among others. Therefore, only a large variability that by far exceeds typical experimental scatter (for these types of tests that is 5–15%) clearly indicates the presence of additional effects (e.g., aggregate or age effect).

Figure 6 shows all relative cone capacities ($v_t(t)$) plotted against the corresponding L.A. coefficients, following the previously introduced marker and color code.

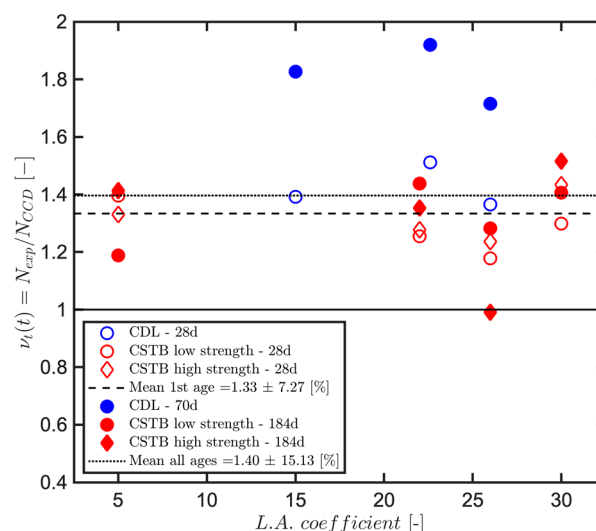


Figure 6. Relative concrete cone capacities for all different concretes and aggregates.

First, it can be clearly seen that the results show an offset from the target value of 1.0, indicating that the default product-specific factor (k) is rather conservative for this anchor type and geometry. The mean relative cone capacity at 28 days is $v_t(28 \text{ d}) = 1.33 \pm 7.27\%$, i.e., the prediction underestimates the real capacity by about 25%. Second, no significant

trend in terms of L.A. coefficient is present. Third, considering the 28-day test results (empty circles and diamond markers) only, the difference between concretes expressed as a COV is only 7.3% and lies in the expected range of experimental scatter. The difference between concretes at the second age is 5.6% if only CDL concretes tested at 70 days are considered and 12.7% in the case of only CSTB tests at 184 days. If the data for all ages are combined, the COV increases to 15%, while the increase is limited to 10% in the case that the 70-day CDL data are not included ($v_t = 1.33 \pm 9.57\%$). A detailed discussion of age and curing effects follows in the next chapter.

Overall, differences in concrete cone capacity exist between different concretes. However, they can be largely explained by corresponding variations in compressive strength. The overall variability in relative concrete cone capacities lies within the range of typical experimental scatter. This conclusion is in agreement with previous studies on other anchor types [35–37] and is now confirmed on a larger data set obtained independently from two research groups for a total of 11 different concretes with 7 different coarse aggregate types and compressive strengths between 27 and 80 MPa.

4.1.3. Age Effect (Comparison between Two Tested Ages)

Concrete aging is a well-known phenomenon and has been intensively investigated in the last few decades [4,5,38,39]. Nevertheless, many questions remain due to the complex multi-scale behavior of concrete and the sensitivity to composition parameters and casting and curing conditions. The previously observed differences in the mean relative cone capacities (if data of all ages are combined, the COV increases to 15%) indicate the existence of other effects that are not fully captured by the design equation. Since the increased COV occurred when all different ages were combined, naturally a potential age-effect is checked by means of a tensile aging prediction ratio, defined as ratio of relative concrete cone capacities for two different ages according to Equation (3):

$$\alpha_{t,age} = \frac{v_t(2nd\ age)}{v_t(1st\ age)} \quad (3)$$

where $v_t(1st\ age)$ and $v_t(2nd\ age)$ are calculated according to Equation (2). If aging and curing effects were fully captured by the design model in terms of compressive strength, α_t would be equal to 1.0. However, it is well known that different concrete material properties age at different rates [18]. Furthermore, concretes with exactly the same mix design can significantly differ in final mechanical properties depending on the curing and storage conditions [5,40]. Figure 7 shows the aging prediction ratios α_{age} for all concretes. On average, predictions at the second age are about 9% higher with a scatter band of approximately 15%. This is in line with the findings previously reported by Ninčević et al. [26]. They reported an increase in conservatism of about 20% for the later age.

In almost all cases, predictions at later ages are more conservative. However, this is not always the case. For two low strength concretes tested by CSTB, the opposite trend is observed. Considering the substantial increase in scatter when tests at different ages are combined, it is likely that aging effects are present. These may depend on intrinsic (e.g., mix design, cement type, aggregate type) and extrinsic (ambient temperature and relative humidity) and require further investigation. The surprisingly large age differences for the CDL concretes which are not observed in the CSTB investigation may be explained by differences in cement type in combination with the ambient storage conditions. CDL used a cement type (CEM II 42.5 N) with ordinary early strength development in combination with relatively low curing temperatures of approximately 15–20 degrees C (288.15–292.15 K), while CSTB used cement characterized by high early strength.

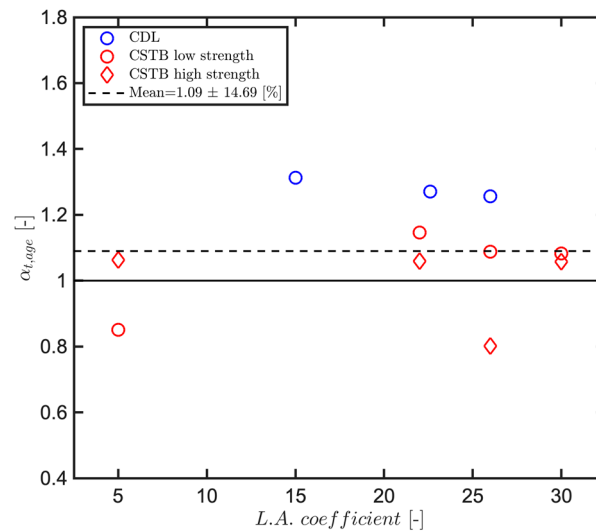


Figure 7. Ratio between relative concrete cone capacities for two different ages.

4.1.4. Photogrammetry—Cone Geometry

The cone shape and curvature depend on the mechanical properties of concrete, which in turn depend on the aggregate type, as does the internal friction angle and aggregate interlock in a formed crack. However, the analysis of all experimentally obtained cone shapes showed no significant difference in cone curvature, regardless of the used aggregate type [32,35,36]. It was not possible to investigate the cone size since all cones localized at the circular steel support with a diameter of $4 \times h_{ef} = 400$ mm (15.7 in.). However, no influence on the load capacity is expected for such support conditions, as confirmed by several experimental studies and suggested by anchor-related codes (assuming a cone diameter of $3 \times h_{ef}$).

4.2. Anchor Results under Shear Loading

4.2.1. Empirical Equation for Concrete Edge Breakout Capacity

The mean concrete edge breakout capacity for anchors loaded in shear towards the edge is given by Equation (4), as proposed by Fuchs et al. [19]:

$$V_{CCD} = k \cdot d_{nom}^{0.5} \cdot \left(\frac{l_f}{d_{nom}} \right)^{0.2} \cdot c_1^{1.5} \cdot \sqrt{f_c} \quad (4)$$

where $k = 1.0$ is the proposed calibration factor (SI), d_{nom} is the nominal anchor diameter, l_f is the effective anchor length embedded in concrete (here, for both anchor types $l_f = h_{ef}$), c_1 is the edge distance, and f_c is the concrete compressive strength measured on a 200 mm (7.87 in.) cube. Note that no difference in shear capacity is expected between bonded anchor and cast-in headed anchor according to the current design approach [19]. It has to be noted that other modified equations exist, accounting for additional geometrical effects (e.g., larger embedment depths or anchor size) while still being based on the concrete compressive strength only. Therefore, only one predictive model is used here for the normalization of experimental shear capacities.

4.2.2. Aggregate Effect at Given Age

In order to investigate a potential aggregate effect on concrete edge breakout, all experimentally observed shear loads are normalized according to Equation (5), yielding a relative shear capacity:

$$v_s(t) = \frac{V_{exp}(t)}{V_{CCD}(t)} = \frac{V_{exp}(t)}{k \cdot d_{nom}^{0.5} \cdot \left(\frac{l_f}{d_{nom}} \right)^{0.2} \cdot c_1^{1.5} \cdot \sqrt{f_c(t)}} \quad (5)$$

Note, all shear capacities are normalized with the compressive strength results obtained on specimens cast in the same batch and tested at the same age. Ideally, the ratio $\nu_s = 1.0$, or scatter around this value in a typical range ($\pm 5\text{--}10\%$), is observed.

Figure 8 shows normalized results where noticeable correlation between L.A. coefficient and prediction is present.

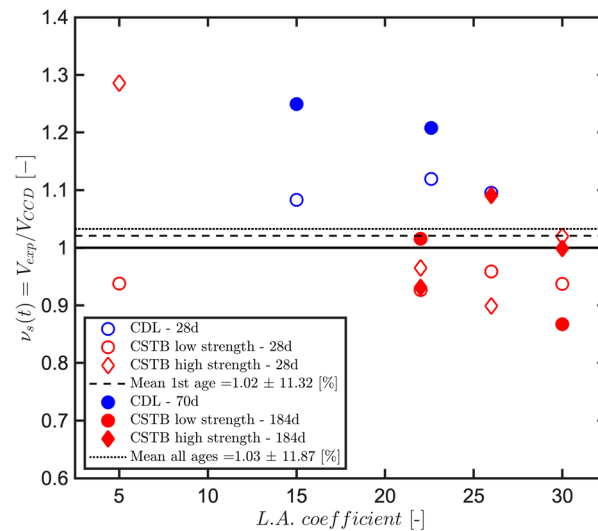


Figure 8. Relative edge breakout capacities for all different concretes and aggregates.

Overall, the experiments slightly exceed the predictions by 2% for the first age and by 3% if all ages are combined. The variability between concretes of about 12% is smaller than observed for anchors loaded in tension and lies at the level observed for each individual test series. However, at closer look, some systematic differences exist. Predictions for CDL concretes are slightly more conservative than for CSTB concretes. These differences can likely be explained by differences in test setups and slab geometries, in addition to concrete-related differences. Furthermore, it is known that the execution of pure shear tests is not trivial. The high scatter might also be caused by the difficulty to completely avoid bending moments as well as the two anchor types used (headed cast-in and post-installed adhesive anchors), even though no differences are expected according to current design models. A comparison for two more edge distances ($c_1 = 50$ and 150 mm) for the CDL concretes is available in [27].

4.2.3. Age Effect (Comparison between Two Tested Ages)

Finally, an effect of concrete age on concrete edge breakout is checked, following the same procedure as used earlier for anchors under tensile loading. The shear age prediction ratio according to Equation (6) is used to evaluate a potential age effect.

$$\alpha_{v,age} = \frac{v_s(2nd\ age)}{v_s(1st\ age)} \quad (6)$$

Figure 9 shows the ratios for all concretes for which two tested ages exist. The mean of all shear prediction ratios is equal to 1.06, denoting an average increase in conservatism with age, although the value remains close to the target value (1.0). If only individual concretes are considered, it can be seen that for some concretes a more pronounced aging effect is observed than for others.

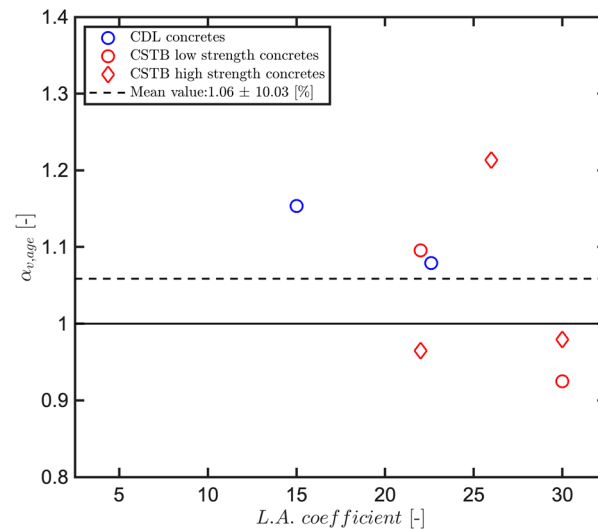


Figure 9. Ratio between relative shear load capacities for all different concretes and aggregates.

4.2.4. Photogrammetry—Edge Breakout Geometry

A careful analysis of half-cone concrete voids, among others supported by photogrammetric mean, revealed no significant differences in breakout body shape as a result of differences in composition or age. All half-cones localized at the steel supports [27], even though the distance between supports was six times the edge distance (also six times the embedment depth).

5. Conclusions

An experimental campaign performed by two different research groups is presented with the aim to investigate a potential effect of aggregate type and concrete age on the load capacity for anchors loaded in tension and shear. The experimental investigation involves anchors installed in seven low- and four high-strength concretes tested at two different ages. The tests on anchors under tensile loading were carried out on headed studs, while shear tests were performed on headed studs and bonded anchors. Based on the experimentally obtained data sets and systematically carried out analysis, the following conclusions are drawn.

Experimentally obtained concrete cone capacities are compared to the current empirical model in terms of concrete compressive strength. Results clearly show that the current empirical model underestimates experimental values by around 20–30% for the first tested age (28 days) for the studied anchor type and geometry.

Relative concrete cone capacities in tension reveal practically minor differences among all tested concretes. The effect of different petrography of the coarse aggregates used in this study is shown to be smaller than the typically expected scatter in this type of structural test. Results show a relative difference between normalized values of ~7% in the case of the 28-day tests. Therefore, it can be concluded that the current empirical model captures sufficiently well the effect of different aggregates.

The analysis of anchor capacities in tension, normalized by the compressive strength determined at the respective age, reveals a systematic increase in conservatism with age for almost all investigated concretes. Based on the mean value for all investigated concretes, predictions at the second age are about 9% higher with a scatter band of approximately 15%.

In the case of anchors under shear loading, similar trends are observed. Differences in coarse aggregate type seem to be reasonably well captured by the current model based on concrete compressive strength. Experimental mean values agree well with the model predictions. While the normalized values scatter more compared to the tensile tests, the scatter between concretes remains smaller than the scatter within individual test series.

Also, in the case of concrete edge breakout, an aging trend is found, leading to more conservative results at later ages. Even though the mean of all shear prediction ratios is equal to 1.06, for some concretes a more pronounced aging effect is observed than for others (up to 20%).

Further studies comprising structural anchor tests for concretes with different cement types and ideally more ages are necessary to confirm the findings and to develop a more systematic understanding of aging effects on anchor performance. Such future studies should also consider different anchor types and variations in the geometry of the problem (e.g., embedment depth, head size, edge distance, etc.) [41].

For both considered failure modes, the analysis shows that the L.A. coefficient is unsuitable to describe the effect of coarse aggregate type on either concrete properties, concrete cone capacity in tension, or concrete edge breakout in shear.

Analyses of concrete cone and half-cone shapes by size measurements (CSTB) or advanced photogrammetric analysis (CDL) showed minor differences related to the coarse aggregate type or age [27,32].

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