YCRETS 2023
YOUNG CONCRETE RESEARCHERS, ENGINEERS & TECHNOLOGISTS SYMPOSIUM

CEMENT & CONCRETE SA

The design and analysis of anchor connections in lightweight concrete

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Abstract

The recent development in environmental studies show lightweight concrete as a suitable building material which aligns with sustainable principles. In terms of anchor design, concrete is the most preferred base material and is well-suited for anchoring; although the frequent use of lightweight concrete in the construction sector suggests the performance of fixing systems in lightweight concrete should be explored.

Anchor connections are used in all facets of the building and construction sector – namely household, structural and industrial fixings. This study explores the concept of anchor design and discusses the contributing factors that affect the overall performance of a fixing system. Innovative designs and alternate building materials prompt new development in the fixings industry, therefore in order to adapt and develop new fixings, one must understand the basics of anchor design.

Keywords: sustainable principles, lightweight concrete, anchor design, fixing systems

1. INTRODUCTION

It is known that solid concrete is the most preferred base material for anchors [3]. However, the importance for lightweight concrete to be identified as suitable base material in terms of anchor technology has been gaining traction within the anchor technology industry [2].

This study explores the theory of anchor design and demonstrates significant concepts through a case study [2]. Base materials, load-bearing capacities, failure modes and installation criteria are introductory concepts used to explore anchor design theory [1]. To showcase the industry development of concrete, an experiment which focuses on the performance of anchor technology in lightweight concrete is conducted.

2. THEORETICAL BACKGROUND

Anchor connections are generally used in steel to concrete connections to transmit loads from one element to another via anchor bolts [3]. The anchor bolts are used to distribute load actions into its base material and are influenced by key parameters such as its base material, load bearing capacities and anchor failures of the most unfavorable anchor [3].

2.1. Base Materials

There are various types of base materials available for anchoring. The most common types are concrete (cracked and uncracked), masonry (composite material composed of hollow or solid brick), boards and panels [4]. Each base material varies in compressive strength which has an influence on the anchor connection [3].

2.2. Load Bearing Capacities

The load bearing capacity of anchors refers to the tensile and shear (and combined tensile and shear) loads applied to an anchor connection [4]. Load actions are transferred via anchor bolts which function on two basic principles: Expansion/Undercut theory or Bonding theory [3].

2.2.1. Expansion/Undercut theory

This principle uses mechanical interlock and friction to hold an anchor into its base material [3]. Mechanical interlock of anchors transfers the load to the base material by locking against the base material [3]. Expansion anchors work on the principle of friction to create a force between the anchor and its substrate [3].

2.2.2. Bonding theory

Chemical anchors rely on bonding between the chemical, anchor and substrate [3]. In this case, the load is transferred from the anchor to the base material via the bond created by the chemical components. A chemical reaction occurs between the epoxy mortars which produce different strengths of chemical bonds [5]. Each chemical mortar has unique chemical components that require curing and drying times [5].

2.3. Failure Modes

Anchor connections fail when the load applied to the anchor connection exceeds its ultimate working capacity [4]. Anchor design is based on understanding the failure modes and providing sufficient resistance within a connection to prevent failures. Failures are classified into four modes: (a) Steel failure, (b) Pull-out failure, (c) Concrete cone failure, (d) Splitting failure. A description of each failure mode is given below [3].

2.3.1. Steel failure

Steel failure is a direct failure of steel, which occurs when the tensile load causes the steel to snap, whilst the contact between stud and base material remains intact [3].

2.3.2. Pull-out, pull-through and pry-out failure

Pull-out failure occurs when the anchor is pulled out of its base material, whilst pull-through failure occurs when the anchor disassembles at the expansion point and pulls out [3]. Pry-out failure occurs when the anchor is removed with excessive shear [3].

2.3.3. Concrete cone

Concrete cone failure refers to when a conical section is developed around the anchor and breaks out from its base material in this shape [3]. The cone is approximated to be 1.5 times the effective depth, with the tip of the cone being the part of stud that's furthest into its base material [6].

2.3.4. Splitting failure

Splitting failure refers to the cracking (or splitting) of a base material due to the incorrect embedment depths [3]. This failure mode is influenced by the spacing and embedment depths of an anchor connection.

2.4. Installation Dimensions for Anchor Bolts

Anchorage depth, spacings, and edge distances have an influence on the load bearing capacity of an anchor connection [3]. Figure 1 illustrates an overall description of the influencing dimensions considered when installing fixing systems: diameter of anchor bolt (d_0), effective depth (h_2), fixture thickness (t), Installation torque (T_{inst}) [3].

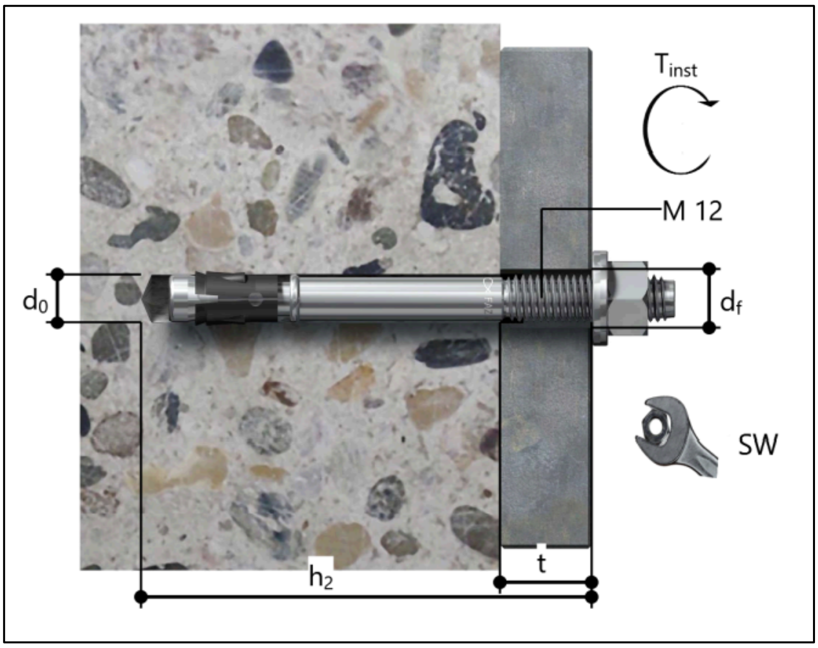

Figure 1: Influencing dimensions for typical anchor connection [3]

3. DESIGN OF ANCHORS

Anchor design involves applying engineering principles to determine safe-working conditions for anchor connections. This is calculated by using partial safety factors and the ultimate failure loads [4].

Partial safety factors are theoretical values which quantify the effect of the different parameters outlined above, on the overall anchor design. The equations shown in Table 1 are extracted from SANS: 51992 Part 4: Design of fastenings for use in concrete [5].

Table 1: Partial safety factors with correlating failure modes [5]

FAILURE MODES	PARTIAL SAFETY FACTORS
	Accidental design situations
STEEL FAILURE – Anchor fastenings	
1. Tension	$\gamma_{Ms} = 1.05 f_{uk}/f_{yk} \geq 1.25$
2. Shear	$\gamma_{Ms} = \frac{1.0 f_{uk}}{f_{yk}} \geq 1.25$ $when\ f_{uk} \leq 800 N/mm^2 and\ f_{yk}/f_{uk} \leq 0.8$
CONCRETE RELATED FAILURE	
3. Concrete cone failure	$\gamma_{Mc} = \gamma_c \cdot \gamma_{inst}$
4. Concrete edge failure	$\gamma_c = 1.2$
5. Concrete pry-out failure	$\gamma_{inst} = 1.0$ $for\ fasteners\ in\ tension\ and\ shear$
6. Concrete splitting failure	$\gamma_{Msp} = \gamma_{Mc}$
7. Pull-out failure	$\gamma_{Mp} = \gamma_{Mc}$

where,

γ_{Ms} = partial safety factor for steel failure
f_{uk} = nominal characteristic steel ultimate tensile strength
f_{yk} = nominal characteristic steel yield strength
γ_{Mc} = partial safety factor for concrete cone, concrete edge, concrete blowout and pry-out failure modes
γ_c = partial safety factor for concrete edge failure
γ_{inst} = factor accounting for the sensitivity to installation of post-installed fasteners
γ_{Msp} = partial safety factor for concrete splitting failure
γ_{Mp} = partial safety factor for concrete pull-out failure

4. CASE STUDY

In order to learn more about the role of lightweight concrete as a base material, a case study is conducted to explore the working capacities of a sample of fixing systems through a series of mechanical tensile loading tests.

A sample of fixing systems, containing four different types of systems are installed in lightweight concrete blocks. A tensile load is applied to each system, and the mode and load at failure is recorded. Each system is installed and tested four times and an average performance result is determined. Using design concepts outlined in the previous section, a design analysis is calculated to determine the safe-working capacities of the various systems.

4.1. Methodology

The information presented in Table 2 show critical data that describes the materials and equipment used for this case study.

Table 2: Test materials & Equipment

MATERIAL/EQUIPMENT	DESCRIPTION
1. Lightweight concrete block	1.1. Dimension: 700x340x120 mm 1.2. Density: 480 kg/m^3 1.3. Compressive strength: 2.58 MPa
2. Fixing systems	2.1. Duo Power Plug & Coach screw 2.2. SXRL 2.3. UX 2.4. Nylon Hammer fix (Green) 2.5. Nylon Hammerfix (Standard)
3. Power tools	3.1. Percussion drill with masonry drill bit. Bit size: 9 mm Bit size: 7 mm
4. Hydraulic tensile tester	4.1. Hydraulic tester with 10 kN calibrated gauge

4.2. Test Setup and Procedures

Figures 2 and 3 illustrates the samples of fixing systems installed and tested until failure. The results are tabulated and shown in Table 3.

The sample set of fixing systems are selected according to the size and length of the plug and screw. The dimensions of each system are chosen with similar characteristics to ensure that the testing and recorded results are fair and unbiased.

Table 3: Results obtained through tensile testing

FIXING SYSTEM		RESULTS	
Type	Dimensions	Failure Mode	Failure load
Duo Power (Duo Line)	ø size: 10 mm Length: 50 mm	1. Pull-out failure 2. Pull-out failure 3. Pull-out failure 4. Pull-out failure	0.2 kN 0.3 kN 0.2 kN 0.2 kN
Duo Power (Duo Line)	ø size: 10 mm Length: 80 mm	1. Pull-out failure 2. Pull-out failure 3. Pull-out failure 4. Pull-out failure	1.6 kN 1.6 kN 1.4 kN 1.4 kN
SXRL (Frame fixing)	ø size: 10 mm Length 80 mm	1. Pull-out failure 2. Pull-out failure 3. Pull-out failure 4. Pull-out failure	1.2 kN 1.4 kN 1.3 kN 1.0 kN
UX (Universal Plug)	ø size: 10 mm Length: 50 mm	1. Pull-out failure 2. Pull-out failure 3. Pull-out failure 4. Pull-out failure	0.8 kN 0.7 kN 0.8 kN 0.6 kN
Nylon Hammer fix (Standard)	ø size: 8 mm Length: 80 mm	1. Pull-out failure 2. Pull-out failure 3. Pull-out failure 4. Pull-out failure	0.1 kN 0.2 kN 0.2 kN 0.2 kN
Nylon Hammer fix (Green)	ø size: 8 mm Length: 80 mm	1. Pull-out failure 2. Pull-out failure 3. Pull-out failure 4. Pull-out failure	0.2 kN 0.2 kN 0.1 kN 0.2 kN

Figure 2: Fixing systems installed and tested: UX (10x80), N H/FIX G (8x80), N H/FIX S (8x80)

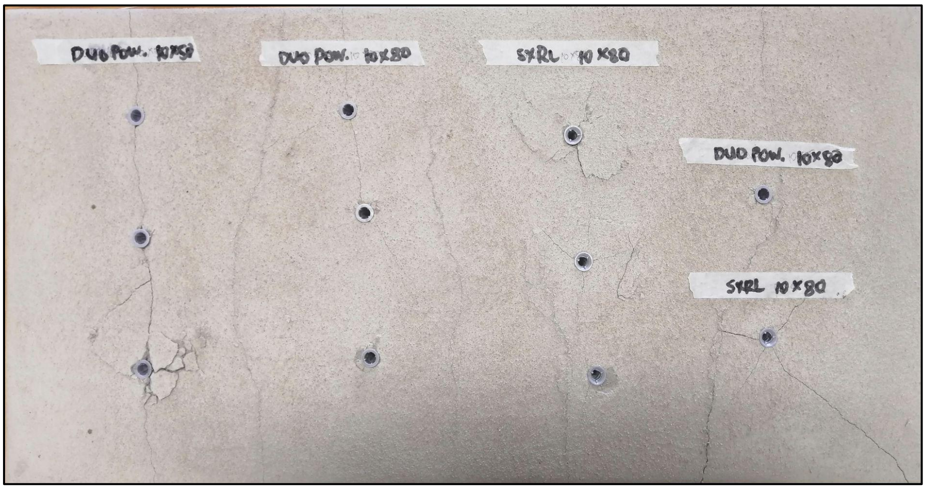

Figure 3: Fixing systems installed and tested: D/P (10x50), D/P (10x80), SXRL (10x80)

5. DISCUSSION OF RESULTS

Figures 2 and 3 illustrate the failure modes of the relevant fixing system. Minor cracks developed in the lightweight concrete block, which questions the structural integrity of lightweight concrete as a base material. Physical inspection of each fixing system indicates that pull-out failure can be identified as the ultimate failure mode.

Table 4: Determination of safe working loads

FIXING SYSTEM	AVERAGE ULTIMATE TENSILE FAILURE LOAD	PARTIAL SAFETY FACTOR	SAFE-WORKING LOAD
Duo Power 10x50	0.23 kN	4	0.06 kN
Duo Power 10x80	1.5 kN	4	0.38 kN
SXRL 10x80	1.23 kN	4	0.31 kN
UX 10x80	0.73 kN	4	0.18 kN
Nylon Hammerfix (Standard) 8x80	0.18 kN	4	0.04 kN
Nylon Hammerfix (Green) 8x80	0.18 kN	4	0.04 kN

Partial safety factors are used to factor the ultimate tensile failure load, as shown in Table 4. The partial safety factors used in the calculations are given by the manufacturer and are adhered to according to each product's technical guidelines for installation [6]. It can be noticed that the Duo Power (10x80) fixing system is able to withstand 1.5 kN (±150 kg) tensile load which yields a safe-working load of 0.38 kN (± 38kg). This type of plug and screw is deemed the best performer in comparison with the remaining plugs and screws in the test sample.

6. CONCLUSION

It is important to discuss and explore the design of fixing systems, since these systems are used in all facets of the building and construction sector. The benefits of lightweight concrete align with sustainability principles and call for innovative fixing systems that are able to perform in variable base materials with high load capacities. The results prove that each fixing system is unique in design and each physical property of the system can be considered as contributing factors to the overall working capacity.

To showcase the recent development with lightweight concrete, various fixing systems are tested, and their performance is studied under tensile loading. For the purpose of this study, the pricing of different fixings systems isn't considered, however, in reality, price has a major influence over the type of fixing system used. This study contributes towards the research and development of anchor technology in lightweight concrete for the building and construction sector.

ACKNOWLEDGEMENTS
The author expresses thanks to Green Crete, UPAT SA (PTY) LTD. and fischer for their contributions towards the completion of this study.

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