Assessing the Impact of Drilling Techniques on the Tensile Strength of Mechanical Screw Anchors in Masonry

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ABSTRACT

Mechanical screw anchors are used for a range of structural connections on masonry buildings, including as part of earthquake retrofit solutions. While extensive research has been devoted to understanding the working mechanisms of mechanical screw anchors into masonry, there is a critical gap in research pertaining to the effects of installation methods on the performance of these anchors. A comprehensive investigation into the impact of drilling methodologies on the performance of mechanical screw anchors in masonry is presented herein. The study encompasses three key stages: i) overarching testing to assess the extent of damage on substrates caused by drilling, ii) blowout and microcrack investigation to quantify pull-out capacity reduction due to these damages, and iii) microcrack investigation under controlled conditions to understand the impact internal microcracking due to drilling on pull-out capacity.

Through extensive experimentation, it was found that the choice of drilling method and the hammer action intensity significantly influence the anchor performance. Rotary-only drilling consistently proved superior leading to higher anchor pull-out capacities and reliability. Light-hammer drilling led to intermediate anchors pull-out performance and hard-hammer drilling led to substantial reductions in anchor capacities and unpredictable outcomes despite its operational speed. These findings underscore the impact of drilling methodologies on anchor performance in existing masonry and emphasises the importance of using material specific tools, such as spear drill bits, to facilitate effective and efficient rotary only drilling in these materials.

1 INTRODUCTION

Mechanical screw anchors are used for a wide range of structural connections, including but not only as part of earthquake retrofit solutions such as to connect timber and steel strong-backs to masonry walls (Dizhur et al., 2017), interconnect the leaf on masonry cavity walls (Graziotti et al., 2016, Tocher et al., 2020), securing of non-structural elements (NZSEE, 2017), wall-to-diaphragm connection (Dizhur et al., 2020, Campbell et al., 2012), connection of existing masonry to new concrete overlay (jacketing), to fiber-reinforced polymers or to moment frames.

Mechanical screw anchors are typically designed relying on a consistent performance of every anchor. However, it has become evident that the drilling methodology can have a significant impact on the capacity of the mechanical anchors installed (Schwenn et al., 2021, Deutsches Institut für Bautechnik, 2002). In addition to the strength of the substrate that is directly related to the anchor performance, the drilling methodology and the type of drill bit employed can create micro-damages inside the drilled hole which further impact the anchor performance. The tip of the drill bit, as the point of contact between user and substrate, is another factor that strongly affects the mechanics of drilling of the hole for anchors installation. The main factors of influence are the drill bit geometry, tip shape, material, and feed rate (Deutsches Institut für Bautechnik, 2002, Uhl et al., 2022).

There are two primary drilling methods: hammer drilling and rotary-only drilling. The choice of the drilling methodology depends on the specific application and the substrate being worked on. Hammer drilling works with principles of pneumatic striking mechanism, whereas rotary-only drilling consists of the drill bit's hard metal cutting edge crushing the material through shear forces (Deutsches Institut für Bautechnik, 2002, Uhl et al., 2022).

The experimental campaign undertaken and presented herein consisted of: (i) investigating the impact of drill hammer action intensity. (ii) conducting a comparative evaluation of the ultimate pull-out capacities of mechanical screw anchors installed using different drilling methodologies. And finally, (iii) proposing a standardised drilling methodology for masonry buildings. The practical insights gained from this study will benefit industry professionals, researchers, and designers alike, providing valuable guidance for future research and practical applications in the field.

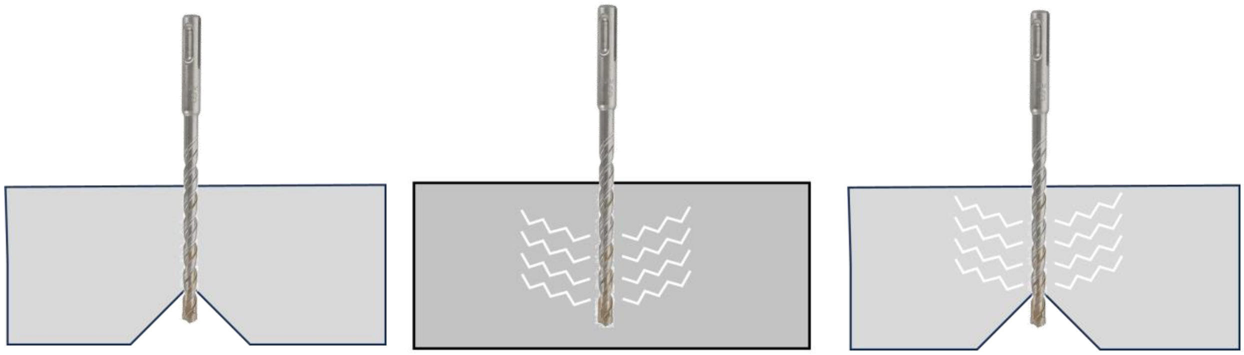
2 SUBSTRATE MATERIALS, DRILLING METHODOLOGIES AND DRILL BITS

The substrate materials used to the investigate drilling methodologies were solid clay bricks (new, 40 MPa, and vintage, 18 MPa compressive strength), concrete masonry units (CMU, 12 MPa compressive strength) and limestone (6 MPa compressive strength). Uniaxial compressive strength tests were undertaken on these materials in accordance with ASTM C67-13 (2013). Two primary drilling methodologies were investigated: hammer drilling and rotary-only drilling.

The type of drills used for evaluation in the assessment of drilling methodologies were chosen based on their prevalence and availability within the industry. Hard-hammer drills, known as SDS (Slotted Drive System), are the most used in the current masonry construction industry. SDS drills are renowned for their vigorous hammer action, which contributes to their effectiveness and drilling speed making them a compelling choice for contractors but also poses the potential for destructive force causing the substrate to break and experience residual microcracks. Light hammer drills work similarly to the hard hammer drills but being a much smaller drill body, the impact hammer action is significantly reduced. Despite that, also light hammer drills can be destructive and their impacts on masonry will be investigated through this research. Rotary-only drills will also be investigated herein, these have no hammer action and they work by cutting through the material.

The drill bits investigated were categorised into two primary groups: (i) hammer action drill bits, and (ii) rotary-only (aka spear) drill bits. Rotary-only drills are not intended to be used with hammer action on and the supporting shank is designed for exclusive use in rotary-only applications. Several drill bits were firstly scrutinised selecting the ones with best performance by drilling into hard clay brick, reaching a selection of 3 hammer action drill bits and other 3 rotary-only (aka spear) drill bits for a more detailed investigation. The edge configuration of the drill bit tip was another essential parameter considered during the selection process.

The extent of damage in the masonry substrate due to drilling remains absent from the literature while it looms large in the day-to-day practices of those working on-site. This damage can manifest in two distinct ways: the sudden and forceful expulsion of material from the rear of the brick (Blowout, Figure 1a), or subtle, internal damage concealed from the naked eye (Microcracks, Figure 1b). The blow-out phenomenon has been related to the use of vigorous hammer action and use of inappropriate drill bits resulting in a reduction of anchor embedment (see Figure 1a). This reduction in embedment subsequently translates to a possible decrease in the anchor's pull-out capacity resulting in a solution that might differ from the original engineer design intention.



(a) Blowout *(b) Microcrack* *(c) Combined blowout and microcrack*

Figure 1. Damage on substrate caused by drilling

3 EXPERIMENTAL TESTING

3.1 Blowout extent using different drilling methods and drill bits

Initial drilling testing was performed on new and vintage clay bricks and CMU to study the extent of the blowout phenomenon. The blowout diameter and depth were measured immediately after drilling using all 3 drilling methods and each of the selected 6 drill bits (using 6mm for consistency). To investigate blowout damage without external interference the bricks and blocks were placed over a basic timber frame and secured with clamps. Each hole drilled was separated by 6 times the hole diameter to assure that the zone of influence of the drill axial and rotary-only impact did not interfere between them. In addition, to understand the practicality of each drilling method, the time taken to drill each of the 540 holes was also recorded.

The results of the 540 tests conducted served as a foundational dataset for comprehending the extent of damage incurred by various drilling methods on distinct substrates. Figure 2 shows evidence that the conventionally used hard hammer drilling method removes a large quantity of material in terms of both depth and diameter. The blowout depth, which is directly related to the effective embedment depth, was observed in new clay bricks to be approx. 10 times larger when a hard hummer drilling was used compared to rotary-only drilling, and 3 times larger when compared to light hammer drilling. For CMU, a similar trend was observed with hard hammer drilling being approx. 7 times larger than rotary-only drilling and 3.5 times larger than light hammer drilling. Overall, the blowout depth measured with hard hammer drilling reached up to 40% of the brick's full thickness, in contrast to rotary-only drilling which consistently maintained blowout depth within the range of 2% to 6%. When a light hammer method was used, a degree of moderate damage was observed, which was considered more substantial than the rotary-only drilling approach.

The speed of each drilling method generally affects user's selection of the drilling method, as a result the fast speed of the hard hammer drilling makes it the most used method on-site. Therefore, the practicality of each drilling method is investigated by recording the time taken to drill each 540 tests (see Table 1). It is important to note that R-4 drill bit on hard clay brick demonstrated complete non-functionality (see Table 1), warranting its exclusion from the evaluation within that specific series. As seen in Table 1, using hard hammer drill resulted as the fastest drilling method. However, the difference with rotary-only drilling was 2s for CMU, 9s for vintage clay brick and 10s for new clay brick as the strongest substrate.

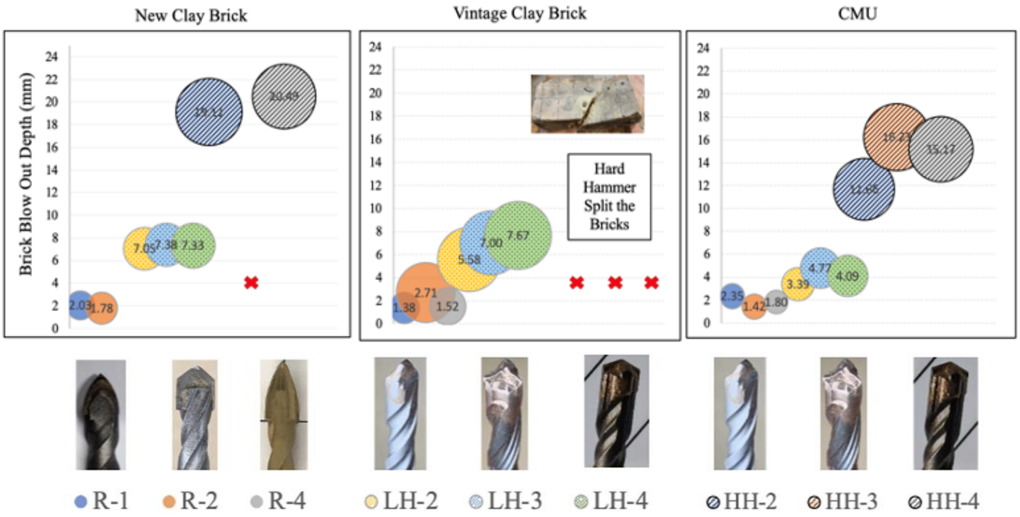


Figure 2.Results in terms of blowout depth and diameter (X denotes brick-split due to hard hammer drilling)

Table 1. Average Time Taken to Drill per Test and R-4 drill bit state (practicality of each drilling method)

Substrates	Average time taken to drill per test (s)				
	Rotary-only	**Light Hammer**	**Hard Hammer**		
New Clay Brick	14	18	4		
Vintage Clay Brick	15	14	6		
CMU	3	4	1	R-4 Before Testing	R-4 After Testing

3.2 Tensile testing using different drilling methodologies

To further explore the impact of drilling methodologies on the pull-out capacity of mechanical screw anchors, an unreinforced ungrouted CMU wall measuring 1.5 meters in height and 4 meters in length was constructed for testing. CMU were used to be able to induce any blowout damage into the shells of the units while drilling reducing the embedment depth. A total of 90 tension tests performed using anchor diameters of 6mm, 8mm, and 10mm installed with a spacing of over 100mm were conducted in accordance with the principles outlined in ASTM C1892/C1892M-22 (2022). 30 tension tests were performed for each of the three drilling methodologies, being 10 tests for each anchor diameter. Pilot holes were drilled with a diameter matching the nominal diameter of the anchor in use and the anchors were installed with an embedment depth of 40mm, equal to the thickness of the CMU shell, which implies that the anchor's embedment would be 40mm if no blowout occurred during the installation process. Each anchor, once installed, was subjected to monotonic tensile loading and the ultimate pull-out capacity and the failure mode were recorded for each test.

The testing setup involved a steel reaction rig with a 200mm diameter frame to accommodate the bearing area. A hydraulic jack was utilised to load the anchor and a load cell to measure these loads. A load distributing frame was connected to the steel reaction rig to reduce any localised wall failures (see Figure 3).

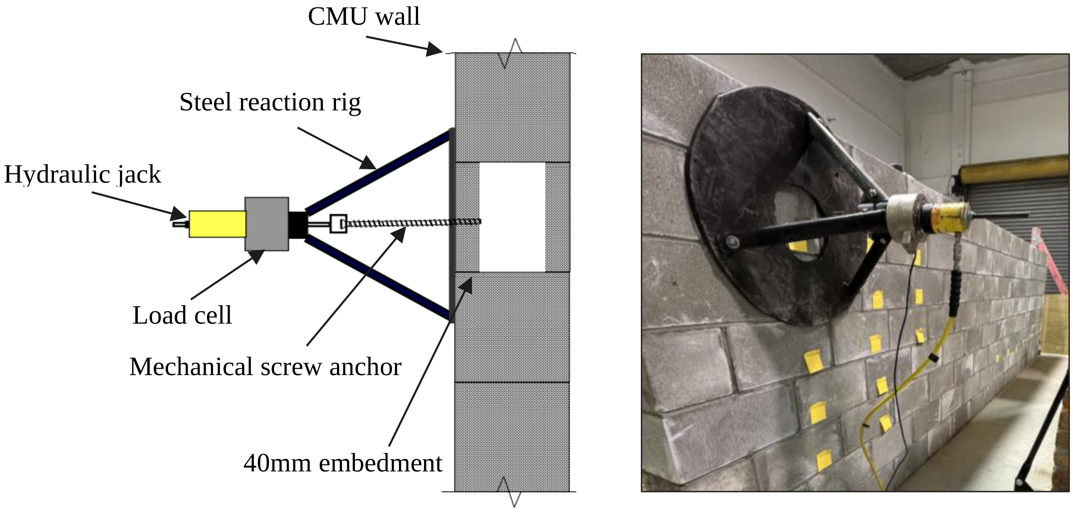


Figure 3 Tensile test setup (CMU wall)

Figure 4 shows the varying pull-out capacities of anchors based on the method of hole installation for the three anchor diameters investigated. All those anchors installed in holes created using a hard-hammer drill consistently exhibited the lowest pull-out capacities with an average of 2.13 kN for Ø6 mm, 2.22 kN for Ø8 mm, and 2.59 kN for Ø10 mm (see Table 2). Anchors placed in holes drilled with light hammer drill show relatively higher capacities with average strength 5.21 kN for Ø6 mm, 4.16 kN for Ø8 mm, and 5.37 kN for Ø10mm, albeit with a notable degree of variability, reaching up to 54% Coefficient of Variation (see Table 2), including the occurrence of ultimate tensile capacity registering at 0 kN when employing the light hammer and hard hammer drilling methodologies. This outcome signifies a complete and critical failure in these cases, where the anchors were unable to withstand any tensile load. In contrast, rotary-only drilling exhibited the highest pull-out capacity with 5.36kN for Ø6mm, 5.81kN for Ø8mm, and 6.57 kN for Ø10mm, and demonstrated remarkable consistency across the tests.

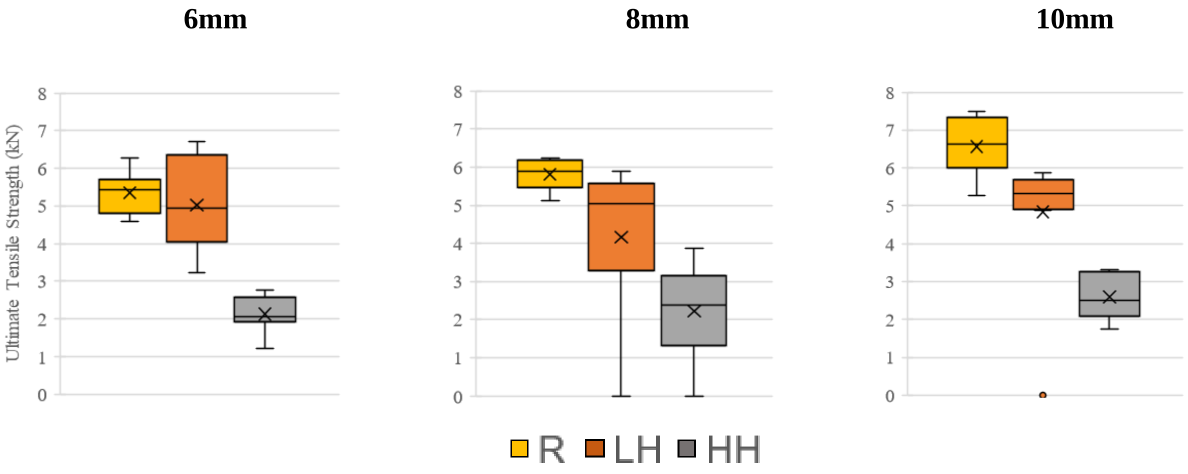


Figure 4 Ultimate tensile strength results (where R is rotary-only, LH is light-hammer and HH is hard-hammer)

The use of hard hammer drilling led to a decrease in capacity of approximately 62% when compared to the results achieved through rotary-only drilling for the three diameters studied. Similarly, the utilisation of light hammer drilling resulted in a significant reduction in pull-out capacity of approximately 27% in comparison to the rotary-only drilling method for 8mm and 10mm diameters, while the reduction for 6mm diameter was 6%.

The anchor’s diameter significantly impacted its capacity, as expected with higher capacities related to greater diameters. Also, larger drill bits tend to cause more extensive blowouts with vigorous hammer action, consequently reducing overall capacity. Although the light hammer drill occasionally produced tests with higher capacities, the overall average remained below that achieved with rotary-only drilling.

Table 2. Ultimate tensile strength results

Average ultimate tensile strength, kN (CoV, %)

Drilling Method	**Anchor Diameter**		
	6mm	**8mm**	**10mm**
Rotary-only	5.36 (10)	5.81 (7)	6.57 (11)
Light Hammer	5.21 (24)	4.16 (54)	5.37 (7)
Hard Hammer	2.13 (22)	2.22 (56)	2.59 (23)

Figure 5 provides an overview of the percentage distribution of tensile failure modes associated with the three drilling methodologies employed on the CMU wall. The predominant failure mode observed across all drilling methodologies was the combined pull-out and cone failure, characterised by the formation of a shallow breakout cone within the substrate and partial withdrawal of the anchor from the substrate material. No instances of steel failure were observed in any of the test specimens, this was expected due to the lower strength of the masonry material compared to the steel anchor. The occurrence of screw pull-out increased with the intensification of hammer action, suggesting that more aggressive hammering induced reduced friction and interlock forces between the anchor and the surrounding material, facilitating the pull-out failure. Cone failure was exclusively observed once in the case of hard hammer drilling.

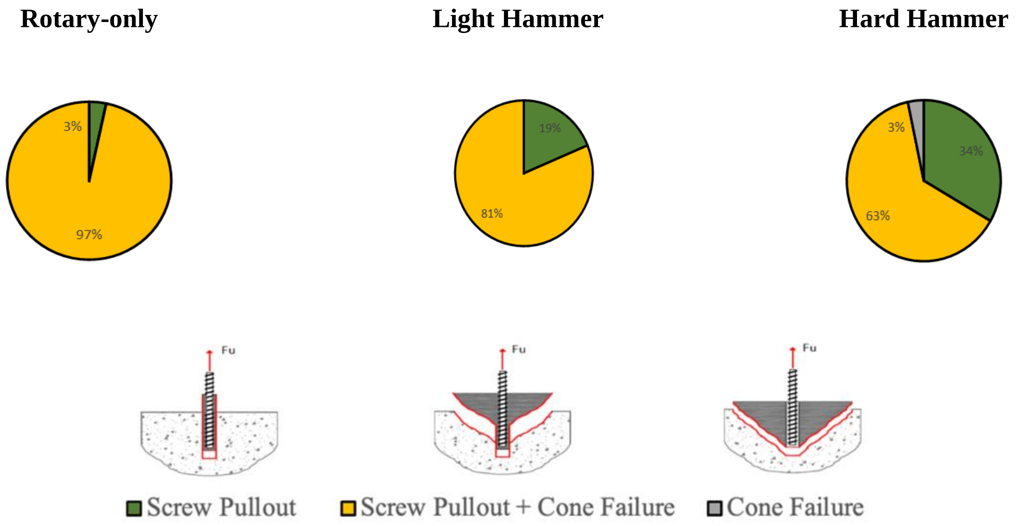


Figure 5. Repetition of occurrence of failure modes in tensile test affected by drilling method

3.3 Tensile testing without blowout using different drilling methodologies

Existing literature indicates that intense hammering action can induce microcracks in the substrate (Schwenn et al., 2021). To understand how microcracks impact the tensile capacity of anchors, it was crucial to create a controlled environment that eliminated the influence of blowout, therefore the anchors were installed in the large blocks of limestone with a 70mm embedment depth using three varying levels of hammer action intensity. The installation procedure involved drilling holes with three different drilling methodologies, then Ø6 mm anchors were installed using a driver. A total of 15 tensions tests were undertaken with 5 tests done per drilling method. The test setup involved a timber reaction rig with wide legs, accommodating for any failures, a hydraulic jack which allowed for manual load application on to the anchor, and a load cell (see Figure 6). The tensile tests were undertaken in accordance with ASTM C1892/C1892M-22 (2022).

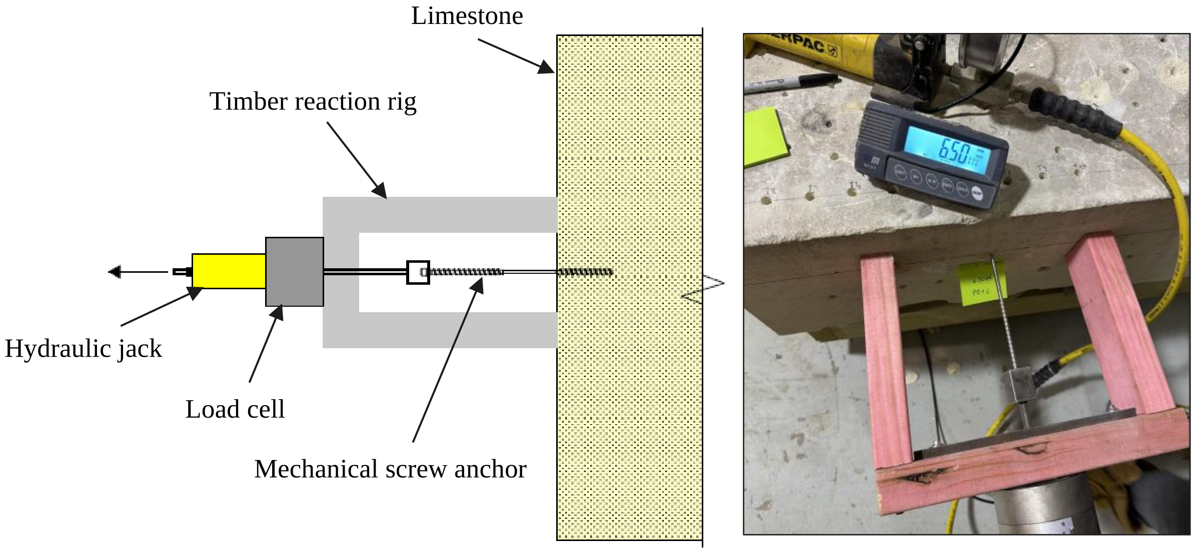
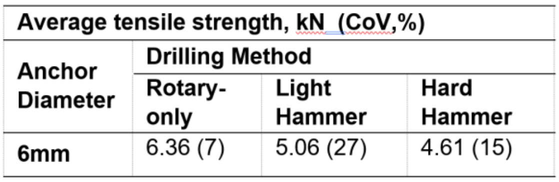


Figure 6. Tensile test setup in limestone

The utilisation of hard hammer drilling resulted in the pull-out capacity being 4.61 kN. Light hammer drilling yields a higher capacity of 5.06 kN, although it comes with a degree of variability, as indicated by the CoV of 27% (see *Figure 7*). Rotary-only drilling resulted in 6.36 kN average pull-out force which is 38% higher than that registered with hard hammer drilling and 25% higher than light hammer drilling (see *Figure 7*). Notably, rotary-only drilling exhibited a high degree of consistency, with a CoV of 7%.



Average tensile strength, kN (CoV,%)			
Anchor Diameter	Drilling Method		
	Rotary-only	Light Hammer	Hard Hammer
6mm	6.36 (7)	5.06 (27)	4.61 (15)

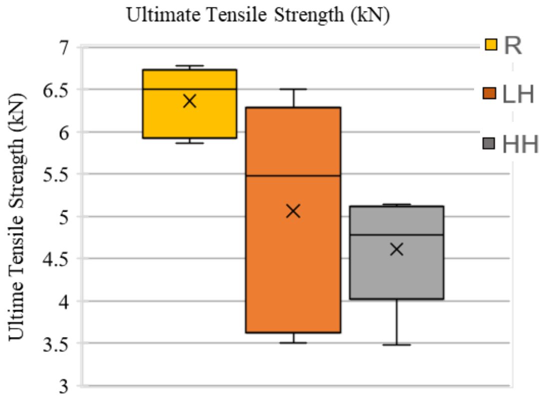


Figure 7. Tensile test results

The failure modes of the pull-out tests conducted on limestone are shown in Figure 8. Notably, when employing rotary-only drilling the predominant failure mode consisted of 100% combined screw pull-out and cone failure. However, the introduction of hammer action into the drilling process leads to the inclusion of screw pull-out failure as a notable component of the failure mode. In the case of hard hammer drilling, 100% of the observed failure modes can be attributed to screw pull-out. Limestone, characterised by its low compressive strength, is damaged easily by the hammering action used while drilling. It became evident that the introduction of hammer action while drilling weakened the mechanical interlock and friction mechanisms of the mechanical screw anchors, significantly impacting the pull-out capacities and the failure modes.

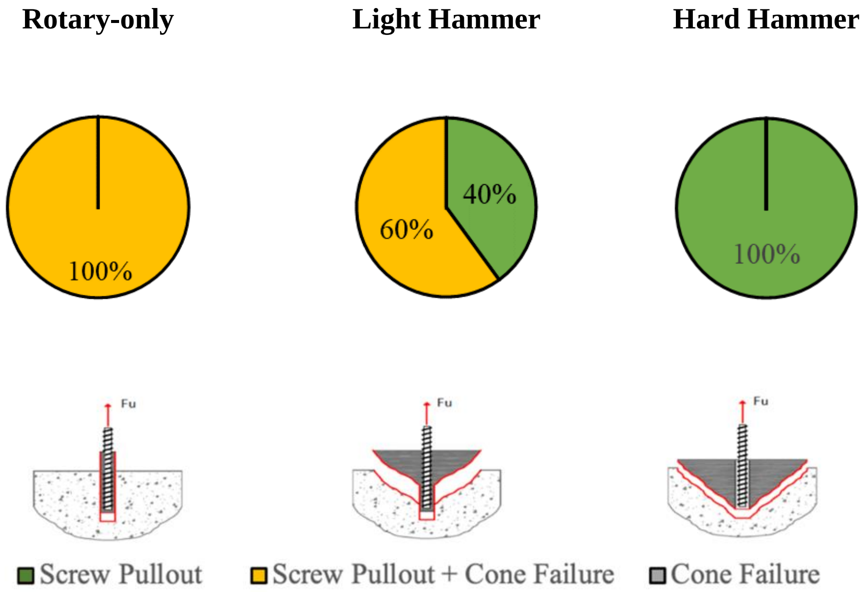


Figure 8. Repetition of occurrence of failure modes in tensile test affected by drilling method

4 CONCLUSIONS

The performed experimental testing served to understand the intricate relationship between drilling methodologies and the performance of mechanical screw anchors in masonry, with a particular focus on addressing the issues of blowout and microcracking. The findings from the different experimental testing campaigns clearly indicate that rotary-only drilling consistently outperforms hard and light hammer drilling, providing higher pull-out capacities, more predictable outcomes, and significantly reducing the risk of blowout and microcracking.

Rotary-only drilling yields minimal damage, resulting in more effective mechanical interlock and friction mechanisms between mechanical screw anchors and substrate, whereas hard hammer drilling, despite its speed, significantly reduces anchor capacities and introduces variability in failure modes, while also increasing the likelihood of blowout and microcracking. Light hammer drilling falls in between these two methodologies, displaying intermediate performance in both anchor capacities and the prevention of blowout and microcracking. It is also noteworthy that the choice of drill bit is a crucial factor, with the two-edge drill bit proving to be the most efficient in minimising damage across substrates and drilling methods while contributing to the reduction of blowout and microcracking in masonry.

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