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Correspondence

Strength and stability of calcite stalactites

The tensile strength of a number of calcite stalactites has been determined by testing to destruction in laboratory conditions in the Civil Engineering Department of Nottingham Trent University (with the kind assistance of Alan Freebury). The sample material was obtained from caves that were due to be destroyed by quarry developments or engineering works, in both the Derbyshire Peak District and the Yorkshire Dales. The two stalactites from the Peak District were long enough to permit multiple destructive tests, and a total of nine results were obtained from the four original samples. Because no comparable data were found elsewhere in the available literature, the results are recorded here (Table 1).

For the tests, each end of each sample was held by slip knots on wire loops that were doubled over so that stress was applied centrally down the axis of the stalactite via the wires to the two slip loops on its opposite sides. Samples were then placed under tensile stress until they failed. This method was preferred to the conventional Brazilian splitting test for tensile strength as the stalactites were not perfect cylinders that could be loaded with absolute uniformity.

Some samples failed in pure axial tension in almost planar fractures perpendicular to the stalactite axis; these were midway between the wire loops at each end, and thereby gave a direct measure of tensile strength. Others failed where they were under radial compression inside the wire loops; the load at this type of failure is an indirect measure of tensile strength, again calculated as the load per unit area of the failure surface. The single stalagmite that was tested failed along a single rhombohedral cleavage plane (at about 60º to the stalagmite axis) that extended through the entire sample except for a thin outer crust. None of the specimens had any taper that was significant to the approximate values interpreted from the results.

The mean tensile strength of the Peak District stalactites (both of which had a fine-grained radial structure with concentric banding) was 4.2 MPa (MN/m^2), while the lowest test value was 3.7 MPa. The re-crystallized stalactite from the Yorkshire Dales had a strength reduced to 2.3 MPa. As the calcite re-crystallizes it loses strength because it develops large planar weaknesses along the rhombohedral cleavage planes.

The very low strength of the old, completely re-crystallized, stalagmite is indicative of the minimum strength that may be found in calcite structures. The value of 0.3 MPa is probably very close to the tensile strength on the c-axis of pure calcite crystals. This complete re-crystallization appears to be common in old stalagmite and flowstone, where it may be recognized by the sparkle of reflected light from large crystal faces at the surface; it appears to be less common in stalactites (other than straw stalactites, which commonly grow as single crystals).

The self-load of a hanging calcite stalactite of uniform diameter imposes a unit stress of 27 kPa per metre length below the point of measurement. A tensile strength of 3.7 MPa (the lowest recorded for the stalactites that had not been re-crystallized – Table 1) would therefore allow the stalactite to grow to about 135m long before it failed under static conditions. A reduction factor of 2 would give a guideline length of nearly 70m for failure under any sort of dynamic loading from disturbance that could include vibration from earthquakes, rockfalls or distant blasting. Stalactites hanging free from the roof of Gruta do Janelao in Brazil are about 40m long, and partly confirm this inherent stability. In addition, the downward taper that is common within thicker stalactites significantly reduces the stress within them, thereby allowing them to grow longer and retain integrity.

Re-crystallisation of calcite reduces its tensile strength where cleavage planes are developed within single crystals (Table 1). The weakest structure is that of a single crystal (with the c-axis aligned with the stalactite axis). This is not common in stalactites. However, it does occur in straw stalactites, where many broken straws on cave floors can be observed to have clean fracture surfaces forming their broken ends. These fractures are commonly oblique to the straw axis, as they are on one of the rhombohedral cleavage planes that distinguish calcite. With a tensile strength of only 300 kPa (Table 1), these would fail at a length of about 11m under static load. Dynamic loading, which could include wind forces on such fragile hanging structures, could reduce the failure length to less than 6m. Such maximum lengths do broadly concur with the observed lengths of straw stalactites that are exceptional and numerous respectively.

These laboratory tests were carried out as part of an investigation to assess the stability of the well-known, very large stalactite in the cave of Poll-an-Ionain in County Clare, prior to engineering works that were planned in its vicinity. Assessments of that stalactite's geometry could only be approximate, but its relatively narrow neck was recognised. Even with that shape, it was estimated that the stalactite has a factor of safety of about 8 under dynamic loading that effectively doubles its static load. The exact structure of the stalactite's internal calcite could not be determined, and a strength reduction to that of the re-crystallised Dales stalactite (Table 1) would reduce the factor of safety to about 5. The distinctive stalactite of Poll-an-Ionain was therefore deemed to be stable, even within an environment of nearby engineering works. It still hangs undisturbed from the cave roof.

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test	material	sample	calcite structure	diameter mm	load kN	tensile strength MPa	failure mode
1	stalactite	Peak #1	fine, radial	37	4.1	3.8	tensile
2	stalactite	Peak #1	fine, radial	32	3.8	4.7	tensile
3	stalactite	Peak #1	fine, radial	36	4.4	4.3	tensile
4	stalactite	Peak #2	fine, radial	43	5.6	3.8	compression
5	stalactite	Peak #2	fine, radial	39	5.8	4.9	compression
6	stalactite	Peak #2	fine, radial	39	5.2	4.3	compression
7	stalactite	Peak #2	fine, radial	42	5.1	3.7	tensile
8	stalactite	Dales #1	crystals 2 – 50mm	28	1.4	2.3	tensile
9	stalagmite	Dales #2	40mm crystal + 5mm crust	60	1.0	0.3	on cleavage

Table 1: *Tensile strengths measured on calcite stalactites in laboratory tests.*