# Building stones of Edinburgh: tests and properties

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Jump to navigation Jump to search

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## Contents



## Building stones of Edinburgh: tests on building stones

**"...it is the properties of these common rock-forming minerals, together with their mode of aggregation within a rock, which determines its hardness, durability, porosity, toughness and strength"**

**Edgar Morton, 1926**

### History

Register House, Edinburgh. Built from

Craigleith Sandstone.

Attempts to assess the strength and forecast the durability of building stone probably date from its beginnings as a structural material. Quarry owners would have wished to give some quantifiable assurance of the performance of a stone to prospective purchasers. Architects would have needed to satisfy themselves and their clients that a particular stone was suitable for the purpose intended. Unfortunately there appear to be few written records of such tests.

George Smith, architect, writing in 1835, records that Robert Adam 'procured specimens from all the quarries in the neighbourhood and after ascertaining their comparative merits, fixed on Craigleith stone for **Register House** [128] (c.1776). It would be of interest to know how such an eminent 18th century architect arrived at his decision. The performance of the stone over two centuries and modern tests on Craigleith stone would vindicate Adam's decision on grounds of durability and strength but what were his reasons for rejecting other stones available at that time? Was he solely concerned with strength and long-term appearance? Was influence brought to bear? Presumably the costs of extracting, transporting and working the stone were not significant factors for such a building, but Craigleith quarry was extensively worked during the following hundred years for many less prestigious buildings.

John Rennie (1761-1821) tested the compressive strength of a one-inch cube of Craigleith stone which failed at 12,346 lb; the moisture content, which would have affected the strength, is not stated. The small size of the sample probably reflects the difficulty of applying an intensive known load evenly to a test piece at that time and we are not told if more than one sample was tested. Craigleith stone was also included in the stones considered by the parliamentary inquiry of 1839 to determine a suitable stone for the construction of the new Houses of Parliament.

Hudson Beare of the University of London, who was later to become Professor of Civil Engineering at the University of Edinburgh, undertook what appears to be the first comparative testing of a wide range of British building stones at the end of the 19th century.

The tests he performed gave the compressive stress required to fracture the specimen, specific gravity, mass (or bulk) density of the stone, water absorption and the coefficient of elasticity (Young's modulus). Importantly he described in considerable detail how the samples were obtained and the tests performed. The latter is important because variations in test methods can cause significant variations in results. Beare also subjected some of the specimens to a freezing test for which he had to rely upon natural conditions; freezing previously soaked specimens by placing them out of doors overnight and thawing them indoors during the day. The test was terminated by a thaw.

Beare obtained his samples for testing by the simple expedient of inviting quarry owners to submit three specimens of stone in the form of two and one quarter inch cubes. We may presume that these were very likely selected samples of the best stone that the quarry could produce and therefore not representative samples. Beare may have restricted the number of specimens from each quarry to keep the tests to a manageable number, bearing in mind the time required to perform the tests. It is likely that he recognised the limitations of testing such a small number of specimens from each quarry but he was seeking comparative values and probably did not expect his results to be quoted unquestioningly and out of context in the years that followed.

Quite apart from the difficulty of obtaining representative values from three small samples of extensive masses of heterogeneous material, the tests must have required careful sequencing to ensure that any one test did not affect a property which was to be tested thereafter using the same specimen. The specimen size was derived by estimating the size of the strongest stone which could be crushed in the 100,000 lb testing machine of University College.

The compression tests performed by Rennie and Beare were on cubes of stone. Nowadays, compression tests are performed on cylindrical columns of stone; normally with a height to diameter ratio of 2.5:1. Such a column would fail at a lower applied load than a cube of identical material. Furthermore, the method of transmitting the load to the test specimen, the characteristics of end plates and any packing pieces, the characteristics of the test machine and the rate at which the load is applied affect results. Therefore a comparison of strength based on compression test results is likely to be misleading.

## Current methods of testing

One of the consequences of the First World War was the acceleration of the decline in the use of dressed stone for building. The development of standard tests on stone was driven by the increasing use of crushed stone for aggregates and the needs of engineers to assess the in-situ strength of rock in mining, tunnelling and excavations. Testing of facing stone for the renovation and construction of buildings continued in research establishments and standard procedures have emerged which have been adopted, with some variants, prior to the publication of British Standards and equivalent internationally accepted standards. Differences in procedures can give different results so a knowledge of the test procedure used is desirable if comparisons are to be made.

However, it is important to bear in mind that, whilst tests can be standardised, stone is a naturally variable material and the measurable characteristics of suitable stones for building fall within wide ranges of values compared with those for products manufactured to satisfy a British Standard. Test results should be regarded as indicative rather than absolute values of a stone's properties. Indeed, there may be considerable acceptable variations within a quarry, giving a choice of compatible stone for differing applications.

An important aspect of Beare's work was that it provided a comparison of the majority of building stones available at that time. His results are reported in full in his paper Building Stones of Great Britain - their crushing strength and other properties. The data tabulated [**add link**] were compiled to provide a similar modern comparison of the properties of sandstones used historically and currently in Edinburgh. Most of the data in this edition are based on tests undertaken at Napier University. They have been supplemented by data made available by the Building Research Establishment and the Edinburgh New Town Conservation Committee and their contributions are gratefully acknowledged. Sufficient tests have been undertaken to show that results from these three sources are compatible within the natural variation of the sandstones tested.

## Tests used as indicators of durability

### Porosity

The majority of stones used for building are sedimentary rocks and, in Edinburgh, sandstones predominate. These stones are composed of grains of sand bound together by natural cements. The spaces between the particles are not completely filled with cement, leaving pore spaces which are normally assumed to be interconnecting. The porosity of a stone is defined as the ratio of the volume of the pore space to the total volume of the stone. The pores vary in size and shape, depending upon the size distribution of the particles and the degree of cementation.

Therefore two stones, having the same porosity, could have very different pore structures; at the simplest, one could contain relatively few but large pores whilst the other contained many much smaller pores. The two stones would have very different absorption characteristics. It follows therefore that a knowledge of the porosity alone is insufficient and the pore size and shape distribution should also be known. Unfortunately this cannot be measured directly and consequently tests have been devised to give indirect measures of these characteristics.

**Water absorption**

The absorption of a stone is defined as the ratio of the volume of water absorbed, when the stone is immersed at atmospheric pressure, to the volume of the stone. It is an indication of the readiness of the stone to absorb water when exposed to the elements. The sample of stone is dried in an oven at between 101°C and 105°C, just hot enough to remove any moisture contained in the pores. The sample is weighed and immersed in water for 24 hours, at the end of which time the surface moisture is removed with a damp cloth and the sample weighed again. The difference in weight gives the mass, and hence the volume, of water absorbed. The ratio of the volume of water absorbed to the volume of the sample is the water absorption and is expressed as a percentage.

In the past this value was sometimes misleadingly quoted as the porosity whereas the total pore space is only partially filled with water during this test.

Quoted values for both absorption and porosity have sometimes been calculated as the ratio of the mass of water absorbed to the mass of the dry sample of stone, expressed as a percentage. Values calculated thus are dependent upon the mass density of the stone, itself a function of the porosity and the constituent minerals. The resulting 'porosity' and `absorption' values are misleadingly low and are of the order of 40% of those calculated by volume; the relative density of porous rocks being about 2.0 to 2.6 that of water.

The porosity is obtained by filling the pores with a non-reactive fluid. The latter is achieved usually by filling the pores with distilled water under vacuum. This method depends upon the assumption that the pores are interconnected and that all can be filled by a liquid from the outside of the sample. This is usually the case with building sandstones but strictly speaking this yields the 'apparent porosity'. The 'true porosity' can be derived by calculation from the mass density of the solid material and the bulk density of the stone.

The relationship between the volume of fluid absorbed and the vacuum applied gives an indication of the pore-size distribution.

**Saturation Coefficient**

A simplified approach is to calculate the 'Saturation Coefficient',' the ratio of water absorption to porosity. A stone with predominantly small pores draws water in by capillary action at atmospheric pressure so that the 'water absorption' approximates to the true 'porosity', giving a high value for the saturation coefficient. Such a stone is supposed to be less durable when exposed to atmospheric conditions than a stone containing a greater proportion of large pores which would have a relatively low saturation coefficient. The latter stone would have a greater volume of free pore space in which crystals of ice or pollutants could form without creating internal stresses.

However, taken on its own, saturation coefficient is not a reliable guide to durability. This measure of purely physical characteristics does not take into account the effects of mineral constituents which may affect durability adversely, for example, the characteristic of some clays to swell over a period of time when exposed on the face of a building. Also a stone of proven durability, like Craigleith, can have a relatively high saturation coefficient combined with a very low porosity; the latter factor in this example being indicative of the high degree of cementation which contributes to the strength of a stone.

**Acid immersion test**

Stones containing calcium carbonate, i.e. limestones and some sandstones are susceptible to attack from the weak acid present in rainfall, particularly in urban areas. A dry sample of the stone is immersed in a 20% solution of sulphuric acid for ten days and the effects recorded.

**Sodium sulphate crystallisation test**

In the Sodium sulphate crystallisation test,' the sample is repeatedly soaked in a solution of sodium sulphate and oven-dried in a humid atmosphere, inducing rapid crystal growth within the pores. A saturated solution may be used for sandstones whereas a 14% solution provides an adequate test for limestones. The test is continued to disintegration or to 15 complete cycles, whichever is the less, and the effects recorded.

The test has been criticised because it does not have a sound theoretical basis. Nevertheless, it provides the most practical means available of testing the potential durability of building stones but it is time-consuming and therefore slow and expensive to undertake.

A second criticism is that stones, which have proved satisfactory in practice, do not survive more than half the cycles and there is not a clear and simple distinction between the satisfactory and the unsatisfactory. Stones that have proved satisfactory in use may appear well down the range of possible values. Reference to Appendix 5 shows the validity of this criticism. The nature of the formation of stone is such that it grades continuously from the weak to the durable and tests reflect this gradation. The saturated sulphate solution provides a particularly severe test and an unsuitable facing stone is likely to show its weaknesses at a very early stage in the test, at as few as two or three cycles. Examples of such unsatisfactory stones have not been identified in use in Edinburgh and therefore do not appear in the data for comparison.

# The mechanical properties of stone strength tests

The property most usually quoted historically is that of compressive strength. Compressive in this context is the means of applying the load by compression along one axis, between the platens of a testing machine; the uniaxial or unconfined compression test. Brittle rocks are not easily compressed and the specimen fails primarily due to shear and, possibly, tensile stresses induced by the application of the compressive load. The maximum load and the nature of the failure depend upon the shape of the specimen and the characteristics of the testing machine. The compression test' requires careful specimen preparation, a powerful testing-machine and is not suitable for all types of rock.

A strength test that has found favour since 1970 is the point-load test. A compressive load is applied through two conical loading points until the specimen splits, failing due to the tensile stress developed perpendicularly to the axis of the applied load. The test may be used in the field because the specimens require only rough shaping with a hammer and the relatively small load required can be applied with the aid of a hand-operated jack. The ease with which specimens can be prepared and tested and the consistency of results means that a high degree of reliability can be placed on the strength index obtained.

**Uniaxial or unconfined compression test**

Nowadays this test is usually performed on cylindrical specimens, using standard diamond drill cores. It is important that the diameter is constant and that the ends are parallel to one another and perpendicular to the axis of the cylinder. This is more difficult to achieve in some rocks than others.

The specimen is immersed in water for 24 hours prior to the test. The length, L and diameter, D, are measured. The specimen is placed between the parallel flat platens of the testing machine and compressed until failure occurs, the maximum load, P, being recorded. The compressive strength is recorded as the load at failure divided by the cross-sectional area of the specimen.'" This method of testing permits the deformation of the specimen to be measured and the modulus of elasticity, E, to be derived.

**The Point-load test**

The specimen of rock is compressed between two hardened steel points until it splits, the failure being predominantly due to tensile stress induced perpendicularly to the plane of loading. The points are hardened steel cones, rounded to a radius of 5mm at their tips. The points may be fitted to a laboratory testing machine or used in a light portable rig, using a hand-operated hydraulic jack to apply the load. Specimens may be pieces of drill core or fragments of rock about 50mm in diameter. The length is normally between one and two times the diameter. Correction factors have been developed for application to results obtained on specimens which are above or below the recommended sizes. The point-load strength index is expressed as P/D2 where P is the load at failure in MN (MegaNewtons) and D is the diameter of the specimen in metres. Some workers have shown a relationship between the point-load index and compressive strength but, in general, insufficient results are available to make other than a generalised relationship.

# Test results for a selection of building stones

| Quarry | Bulk Density kg/m3 | Point-load strength MN/m2 | Porosity % | Absorption% | Saturated sodium sulphate test cycles | Saturated sodium sulphate % loss | Acid resistance % loss |
|---|---|---|---|---|---|---|---|
| Binny | 2175 | 1.1 | 16.2 | 11.2 | 10 | 100 | c |
| Blaxter | 2173 | 1.8 | 16.5 | 11.4 | 15 | 87 | u |
| Catcastle | 2240 | | | 9.5 | 15 | 55 | u |
| Clashach (standard) | 2346 | 9.0 | 9.2 | 5.2 | 15 | 0 | u |
| Clashach (coloured) | 2007 | 1.9 | 22.5 | 17.1 | 15 | 17 | u |
| Corncockle | 2130 | 0.8 | 18.8 | 13.1 | 8 | 100 | c |
| Corsehill | 1990 | 1.9 | 22.0 | 14.8 | 15 | 24 | c |
| Cragg | 2170 | 1.4 | 16.7 | 12.9 | | | u |
| Craigleith | 2220 | | 13.5 | 6.8 | 15 | 30 | u |
| Craigmillar | 2350 | 3.2 | 9.2 | 8.0 | 12 | 100 | v |
| Cullalo | 2160 | 2.6 | 18.4 | 11.2 | 15 | 15 | u |
| Darney | 2180 | 2.0 | 17.6 | 10.3 | 10 | 100 | u |
| Doddington | 2060 | 1.7 | 20.2 | 15.9 | 15 | 65 | u |
| Dunhouse | 2165 | | 18.4 | 11.3 | 15 | 67 | u |
| Dunmore (new) | | | 17.3 | | 15 | 23 | |
| Gatelawbridge | 2037 | 1.7 | 22.6 | 15.8 | 8 | 100 | c |
| Grange | 2120 | 0.7 | 19.5 | 15.1 | 15 | 57 | u |
| Hailes | 2223 | | 14.5 | 10.9 | 15 | 15 | u |
| Hawkhill Wood | 2370 | 3.0 | 10.1 | 7.1 | 15 | 8 | v |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Hermand | 2210 | 2.0 | 15.1 | 11.2 | 15 | 100 | u |
| Lazonby | 2260 | 2.0 | 13.9 | 9.1 | 15 | 35 | c |
| Locharbriggs | 2210 | 1.5 | 15.1 | 11.2 | 15 | 100 | u |
| Newbigging | 2130 | 0.6 | 18.9 | 12.6 | 10 | 100 | v |
| Plean | 2180 | 1.3 | 17.7 | 14.4 | 6 | 100 | u |
| Prudham | 2150 | | 19.4 | 11.8 | 15 | 70 | u |
| Ravelston | 2630 | 3.8 | 3.6 | 2.6 | 15 | 0 | v |
| Ravelston No. 2 | 2280 | 3.1 | 13.8 | 8.3 | 15 | 11 | c |
| Spinal | 2700 | 16.2 | 0.5 | 0.4 | 15 | 0 | u |
| Spynie | 2070 | 3.8 | 17.9 | 12.2 | 15 | 6 | u |
| Stainton | 2220 | 2.0 | 14.5 | 9.6 | 11 | 100 | u |
| Stancliffe | 2240 | 2.2 | 12.1 | 9.2 | 12 | 100 | u |
| Stanton Moor | 2200 | 1.2 | 16.0 | 13.1 | 15 | 83 | u |
| Stoke Hall | 2346 | 2.0 | 10.5 | 8.2 | 15 | 73 | u |
| Wellfield | 2310 | 3.0 | 11.9 | 8.4 | 15 | 61 | u |
| Woodkirk | 2270 | 2.2 | 13.7 | 11.3 | 15 | 82 | v |



Category:

- Mineral resources

# Navigation menu

## Personal tools

- Not logged in
- Talk
- Contributions
- Log in
- Request account

## Namespaces

- Page
- Discussion

☐

## Variants

## Views

- Read
- Edit
- View history

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