Testing the durability of limestone for Cathedral façade restoration

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Abstract

This research aimed to specify an optimum replacement stone for Truro Cathedral. A variety of petrographically and visually similar material to the original Bath stone was initially selected. The stones were subjected to 3 different durability tests; Sodium sulphate crystallisation and large scale testing with both accelerated and climatic freeze-thaw cyclic loading.

The most suitable stone was determined as the one with the best performance characteristics overall.

Keywords

Restoration, weathering, Oöidal limestone, freeze thaw, durability

Introduction

Truro is a historic town in the south of the county of Cornwall in the United

Kingdom. Truro Cathedral (Figure 1) was built in the period 1880 to 1910 to the designs of J L Pearson, a leading architect of the Gothic Revival style. The majority of the cathedral is constructed of the local Carnsew granite from near Mabe Burnthouse (near Penryn, Ordnance Survey SW 762 339), with the piers, groins, arches, ribs, moulded and carved work from a Bath stone. The name 'Bath Stone' has been given to a range of strata which have been quarried and mined around Bath. All the beds are within the Great Oölite Group of the Middle Jurassic (JEFFERSON 2001).

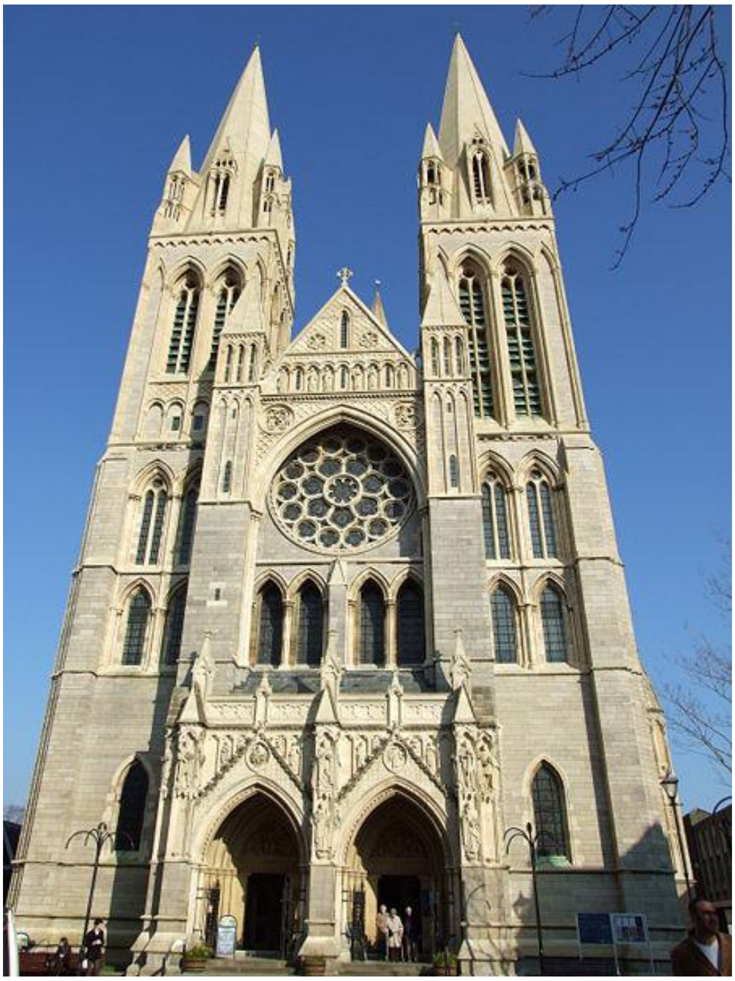

Figure 1. View of Truro Cathedral. (WEBB, 2007)

The original stone from Box was the durable freestone from the Combe Down Oölite. During the 19th century however it is believed that the stone termed

Box came mainly from the less durable Bath Oölite, the stone having reportedly been discovered during the driving of the Box Railway Tunnel (centred on Ordnance Survey ST 838 690). Pearson specified Box Ground as it was seen to be a durable Bath stone, however stone from the Box railway tunnel, which is of extremely poor durability, rather than the more durable Box Ground appears to have been utilised. Box Ground is no longer available and has not been available for some time, therefore there were problems with identification of a suitable replacement stone for the Cathedral.

The Bath stone in this building are weathered variably. Some parts of the fabric appear to be in very good condition, whilst others have disintegrated completely (Figure 2). Investigation of the fabric by Jefferson Consulting for English Heritage concluded that there was no apparent correlation between the degree of exposure and decay levels and it was concluded that there was probably a wide variation in the durability of the stone itself. This latter hypothesis was further investigated through much more detailed examination of a selection of six stones in 1999. The stones conformed to the typical visual and petrographic description of Bath Stone although there were variations in the sizes and composition of the clastic and matrices of the stones. However an obvious reason for selective decay was not discerned (JEFFERSON 2001).

The most recent repairs predating 2005 were undertaken with Upper Jurassic age Savonnières limestone from Savonnières-en-Perthois. This selection, however, was not made on the basis of systematic analysis. Jefferson

Consulting concluded that although the composition of the Savonnières limestone is, in general terms, similar to the Bath stone in the cathedral, being composed of oöids with some shell, its porosity is quite different to that of the original material, in that it has a much more open texture (JEFFERSON 2001).

Figure 2. Weathered statue. (Truro Cathedral, 2005)

In 2005 a 15 year repair and restoration programme was scheduled to commence at Truro Cathedral. The majority of stone work is at high levels, which adds to an already expensive process; the overall cost initially estimated to be a little over £3.6m (TRURO CATHEDRAL, 2005). English Heritage requires the replacement of like for like, but in this case it would be impossible as the more durable Box Ground, the stone originally specified, is no longer available. The Cathedral and English Heritage therefore commissioned a research project at Sheffield Hallam University. The purpose of this project was to identify a material which was more durable than the Bath stone used in the Cathedral, since the original had lasted barely a century. The replacement stone should also have a similar appearance and be petrographically and chemically similar to the original material (JEFFERSON 2001).

Potential Replacement Stone - General considerations

Testing of stone to assess potential durability in the built environment is a difficult task, due to its long lifespan and the many potential mechanisms of decay which may operate upon it over time. Replacement stone should be similar to the existing fabric of a building, taking account of the physical and chemical conditions within the existing stonework. Insertion of a material which has a different chemistry, or has a substantially different porosity or mechanical strength, can potentially create a situation which will result in even further damage to the original fabric (WOOD, *pers comm*.). To meet the replacement criteria for Truro Cathedral, English Heritage specified that the new stone would have to be an uncompacted oöidal limestone, the oöids being free-floating or in point contact with each other and the cement in the stone should be microspar. The porosity of the stone should be a close match to the original and any micritic material in the matrix should be minimal. The appearance of the stone in hand sample should be finely oöidal and uniform. The colour should be pale greyish orange, about 1OYR 8/3 on the Munsell® colour scale (JEFFERSON 2001).

Durability

The process of weathering is still the subject of considerable debate and discussion (INGHAM 2005). At the time of testing there were few pre-existing British Standard tests for the durability of building stone. Standards such as BS 5642-2:1983 (BSI 1983) outline testing for natural stone cills and copings using sulphuric acid were felt to be inappropriate in the assessment of limestones and BS EN 12371: 2001 which uses a regime of freezing in air and thawing in water (BSI 2001) were not felt to be representative of the exposure conditions likely to be encountered by the masonry in the cathedral. In addition there were many established tests such as the sodium sulphate crystallisation test developed at the Building Research Establishment (ROSS & BUTLIN 1992), and methodology for frost testing defined by CERAM (formerly the British Ceramic Research Association, and now CERAM research) for testing the frost durability of bricks (PEAK & FORD 1984). European standards do include frost testing and there was considerable debate on the validity of the test results particularly for natural stone (INGHAM 2005). In addition to more commonly used procedures, the durability of potential stones was therefore assessed using advanced environmental testing techniques. This is a different concept to traditional stone test methods which attempt to measure features of the rock, such as porosity and relate this to durability. Consideration of only one physical property to predict durability cannot be used in all cases, as weathering reactions are much too complex to be assessed in such a simplistic manner (TAYLOR-FIRTH & LAYCOCK 1998). The specialised methods utilise test panels, constructed of mortared blocks of stone, to simulate the action of the weather on the façade of a building over a period of time. Traditionally, laboratory tests are carried out on small samples which may, in some cases, bear little relationship to the large masonry blocks used within the fabric of a building (LAYCOCK 2002). Thus the attempt is made to overcome this limitation by building panels on a more realistic scale, as is standard practice for tests used by CERAM for bricks (PEAK & FORD 1984).

Materials

The samples shown in Table 1 were selected for further testing by Jefferson Consulting (JEFFERSON 2001) based on a detailed assessment of petrographic properties. The names of specific samples have been removed, although generic descriptions have been left in for information. Table 2 summaries average porosity and saturation co-efficient of samples received for testing.

Sample	Petrographic summary	Further information
1	Essentially an oöidal limestone, containing quantities of other materials such as coated grains, stromatoporoids and fragments of shell, echinoids and corals. Oöids are typically about 530 μm in diameter, stromatoporoid fragments as large as 4 mm in length and broken fragments of shell and other organisms can be as small as 150 μm. Compaction of the sediment prior to cementation varies. The cement ranges from microspar to sparite, although the latter tends to predominate. The porosity tends to be confined to micro-porosity in the laminae of the oöids.	A French Jurassic limestone. This appeared to offer a good petrographic match.
2	Sample consists of oöids and other grains in a sparitic matrix. However, many of the oöids, which tend to be between about 800 μm to 900 μm in diameter, have become very diffuse due to micritisation of the laminae. Rounded grains, which range in diameter from about 450 μm to over 2mm, are normally enclosed in a coarse sparitic cement, there are patches of micritic mud containing quantities of fine-grained broken fossils fragments. These patches are up to about 2.5 mm in diameter. The porosity in the stone is largely restricted to micro-porosity in the oöidal laminae, although some macro-porosity occurs where complete spherical grains have disappeared due to solution.	Possibly not aesthetically compatible with the Bath stone in the cathedral, this material has gained a reputation as a good building material.

3	Oöidal limestone, consisting largely of oöids between about 350 μm and 900 μm in diameter. There are also quantities of well-rounded intraclasts of penecontemporaneous sediment, some of which have surface coatings of calcitic laminae, others which are uncoated. Rounded shell fragments range in size from small fragments up to pieces over 2 mm in length. Some of these also have a thin calcitic coating. The oöids and other fragments are in point contact with each other, the cement between them being microsparitic. The crystal size within the spar ranges from about 20 μm up to 700 μm. The macro-porosity is low. However, the micro-porosity, which is largely confined to the oöidal laminae, is high.	The source of this sample has recently been re-opened
4	Sample consists largely of oöids, although appreciable numbers of coated grains also occur. The oöids have diameters between about 300 μm and 900 μm, the coated grains having a slightly larger range of between about 220 μm and 1.3 mm. Occasional fragments of echinoid, up to 950 μm in size are present and, although shell fragments do exist in the sample, they tend to be relatively small and are often recrystallised in the matrix. This cement is micro-sparitic, with individual crystals ranging from about 20 μm to 350 μm in size. Constituent grains tend to be 'floating' in the matrix rather than being in point contact. Porosity is restricted to a micro-porosity in the oöidal laminae, but this is not very great.	This compact close-grained stone is often considered more suitable for interior, rather than exterior use. However, it has been used extensively for exterior ashlar, apparently quite successfully.
5	Poorly sorted stone consisting predominantly of fragments of shell, calcareous algae, intraclasts of contemporaneous sediment, pieces of broken echinoid and with some oöids and coated grains. Grain size is very variable, ranging from less than 500 μm to more than 1.75 mm. The grains tend to be in point contact and the intervening cement is frequently micritic. The porosity of the stone is largely restricted to areas where the nuclei of oöids or coated grains have been lost, or to microporosity in some of the algal coatings on grains.	This is a slightly shelly and harder stone than many Bath stones and has a good reputation for exterior work.
6	Although containing oöids, this stone is a mixture of these particles together with coated grains, fossil fragments, intraclasts and algal masses, none of which are a predominant sediment type. The sediment is also poorly sorted, particles ranging in size from about 130 μm to 2.2 mm. The oöids and coated grains tend to be the smaller components, ranging in diameter from about 480 μm to 800 μm, whereas the intraclasts of penecontemporaneous sediment can be between about 1.3 mm and 2.2 mm in length. Echinoid fragments up to. 1.5 mm in diameter and shell fragments up to 2 mm in length are also present, as are foraminifers. The masses of filamentous calcareous algae can be up to 1.3 mm in diameter. The sediment is relatively well packed although there is no evidence for distortion of the components due to compaction. The cement in the pore spaces between the grains is a mixture of micrite and micro-sparite, the latter appearing to be the result of crystallisation of the former. The porosity is moderate, being a mixture of macro-porosity, where oöids and other particles have been dissolved and micro-porosity in the laminae of the oöids and coated grains.	This is what is often considered a typical and, reportedly, durable, oöidal Bath stone.
7	This is a silicious oöidal limestone. Quartz grains sub-rounded to sub-angular between 90 μm and 260 μm in diameter and concentrated in layers about 1.75 mm thick in the stone, where the they can constitute up to 10% of the rock. Overall concentration of silica about 3.75%. Oöids are between about 300 μm and 1mm in diameter. Echinoid fragments up to about 1.2 mm in diameter and shell fragments well over 3 mm in length have also been noted. The constituent fragments from which the stone is composed are 'floating' in a uniformly crystalline micro-sparitic matrix 85 μm to 175 μm in diameter. The porosity of the stone is low to moderate in the section studied, consisting of a macro-porosity where oöids have been dissolved away, to a micro-porosity related to the oöidal laminae.	Although not a true Bath stone, coming from the Cotswolds east of Cheltenham rather than the Bath area, this stone has favourable petrographic properties and an acceptable appearance.

8 Control	Predominantly oöids with some coated grains, set in a micro- sparitic matrix. The grains range in size from about 350 μm to 1mm, being typically 500 μm to 600 μm in diameter. Oöids micritised and tend to be in point contact with each other. The porosity of the stone is largely a micro-porosity confined to the oöidal material.	Control sample from the North Porch of the Cathedral

Table 1. Petrography of the samples tested. Taken from report to English Heritage

(JEFFERSON 2001)

Sample	Average Porosity	Standard Deviation of Porosity	Average Saturation co-efficient	Standard Deviation of Saturation co-efficient
1	14.22	0.64	0.87	0.05
2	12.94	3.76	0.81	0.09
3	27.20	1.92	0.78	0.05
4	21.55	2.82	0.83	0.02
5	24.05	4.34	0.77	0.07
6	24.75	1.59	0.79	0.05
7	27.78	1.45	0.71	0.02
8	30.09	0.60	0.78	0.02

Table 2. Porosity and saturation co-efficient of the samples shown in Table 1. (Method in ROSS & BUTLIN 1992)

Stone Testing

In addition to the salt crystallisation test (ROSS & BUTLIN 1992), the following experiments were used

- Freeze-thaw test method to draft method in BS EN 772-22 (BSI 1999)
- Climatic simulation chamber

The freeze-thaw test to BS EN 772-22 (BSI 1999) utilises the CERAM (the trading name of British Ceramic Research Ltd) research chamber, which is 1.9m by 2.0m on plan and 1.2m high (external dimensions) with the outer skin having 80mm of insulation between external (ambient) and internal conditions. Two sets of two stone panels, where each panel had a length of 560mm and a height of 740mm, were constructed at one end of the chamber (Figure 3). The panels were isolated thermally from the laboratory. The standard test, first described by Peake & Ford (1984), lasts for 100 cycles (10 days). The elements of each cycle are given in Table 3. In general, a durable brick (e.g. an

Engineering class brick) can be expected to be undamaged after 90 cycles (PEAKE & FORD 1984), however it is anticipated that the Cathedral replacement stone would be substantially undamaged even after the end (100 cycles or 10 days) of the standard test. Here, the standard test was continued to a total of 200 cycles (20 days) to monitor any progressive decay.

Ceram Research cycle	Element	Notes
Pre-conditioning	Soak	7 days at +20ºC
	Pre-freeze	6 hours at -15°C
Freeze-thaw cycle	Thaw	20 minutes from -15º to +25ºC
	Rain	2 minutes
	Drain	2 minutes
	Freeze	120 minutes +25ºC to -15°C
	Cycles per day	10

Table 3: Basic CERAM research cycle (PEAKE & FORD 1984)

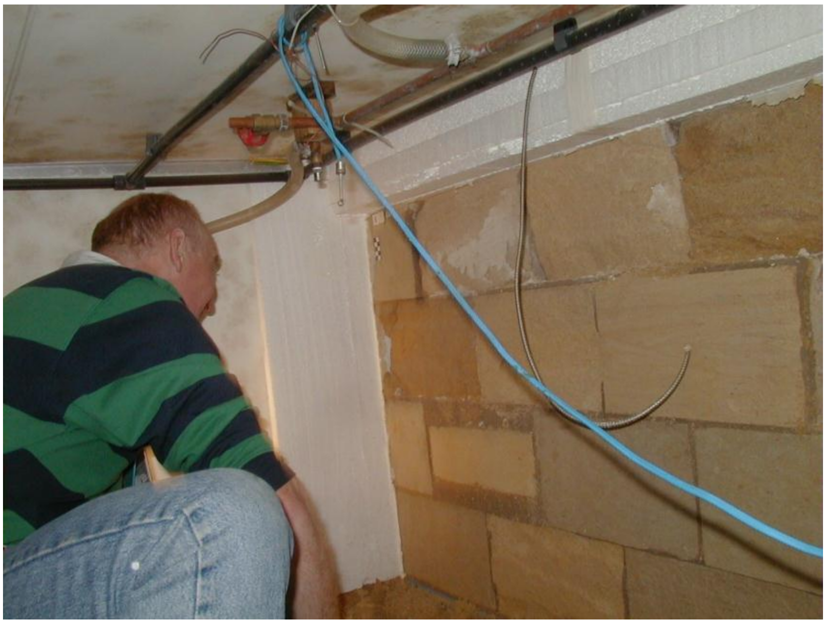

Figure 3. Inspection of test wall in CERAM test chamber

The climatic simulation chamber at Sheffield Hallam has been fully described in the literature (TAYLOR-FIRTH & LAYCOCK 1998, TAYLOR-FIRTH & LAYCOCK 1999 LAYCOCK 2002) and gives control over both interior and exterior conditions to more closely mimic likely weathering elements. The simulator itself is composed of two chambers each of dimensions 4m long, 3m wide and 2.6m in height. A wall was constructed which separated the two chamber halves and contained 8 samples of each of the stone types to be tested, a total of 64 blocks (Figure 4). The sample sizes were 350x200x200mm for full blocks and 170x200x200mm for half blocks and a mortar joint of 6mm was used. Typically the stone supplied from the North Porch of the Cathedral was of more irregular shape and variable in size, averaging approximately 350x190x150mm and thus required the use of a larger mortar joint to keep coursing level.

Figure 4. Inspection of test wall in Climatic Simulation test chamber

It has been noted in several other cases where a much harder, lower porosity or more resistant stone is used to replace a much softer stone that the original stone in contact with the repair appears to degrade far faster (WOOD *pers. comm.*). In order to investigate this, samples in both the Ceram test and the Climatic Simulator were arrayed such that each stone type was in contact with the Box Stone Cathedral. Additionally each of the samples of the proposed replacement stones were in contact with each of the other replacement stones in order to ascertain whether significant damage was caused by this juxtaposition.

Fenex hydraulic lime from Telling Limes was used with sand from Bardon Aggregates, as specified by English Heritage. This was considered to be the strongest acceptable mortar to prevent sacrificial weathering during testing, in effect to prevent an over-weak mortar from failing in preference to the test materials.

The weathering conditions on one side, denoted as the external face, are shown in Figure 5, whilst the other internal face was maintained at 5ºC. Driving rain is created by surface wetting and pressurisation as used in BS 4315-2 (BSI 1970), with the constant air pressure difference of $250N/m^2$ (25mm H_2O) being equivalent to the dynamic pressure head of a 20m/sec wind speed. The constructed wall was allowed to cure at ambient temperature for 28 days, then exposed to 28 days of 'autumnal' conditions, which preceded the realistic freeze-thaw cycling. This was denoted as ‘Atlantic’ type winter conditions and consisted of high humidity in combination with low temperatures. These are known to be more damaging than low humidity freezing events (TAYLOR-FIRTH & LAYCOCK 1998). Anecdotally it has been reported that it is possible to ‘taste the salt’ in the driving rain incident on the Cathedral tower. It is known that such coastal environments provide a more aggressive weathering environment (MOTTERSHEAD 2000). Analysis of the stone samples removed from the Cathedral found that chlorides were higher than expected in material removed from the SE parapet at 0.5% by weight at a depth of 15mm, but far lower at 0.04% by weight at 15mm depth in stone recovered from the SW parapet. Rain water samples were collected by the Dean and Chapter of Truro Cathedral, with subsequent tests indicating a NaCl salt concentration of 0.0105 % by mass. To model the salt level found, the water supply was chilled to 4ºC and contaminated with salt at the same concentration.

Winter simulation involved a cycle of weather Figure 5, based on 30 years of weather data from the Meteorological Office St. Mawgan site approximately 25 km to the NNE of Truro. Conditions were generated for a 3 day cycle repeated initially for 100 days, and then, as little degradation had occurred, for a further 100 days, giving a total of 800 events below freezing. At intervals the climatic simulator wall was subjected to driving rain conditions as described previously.

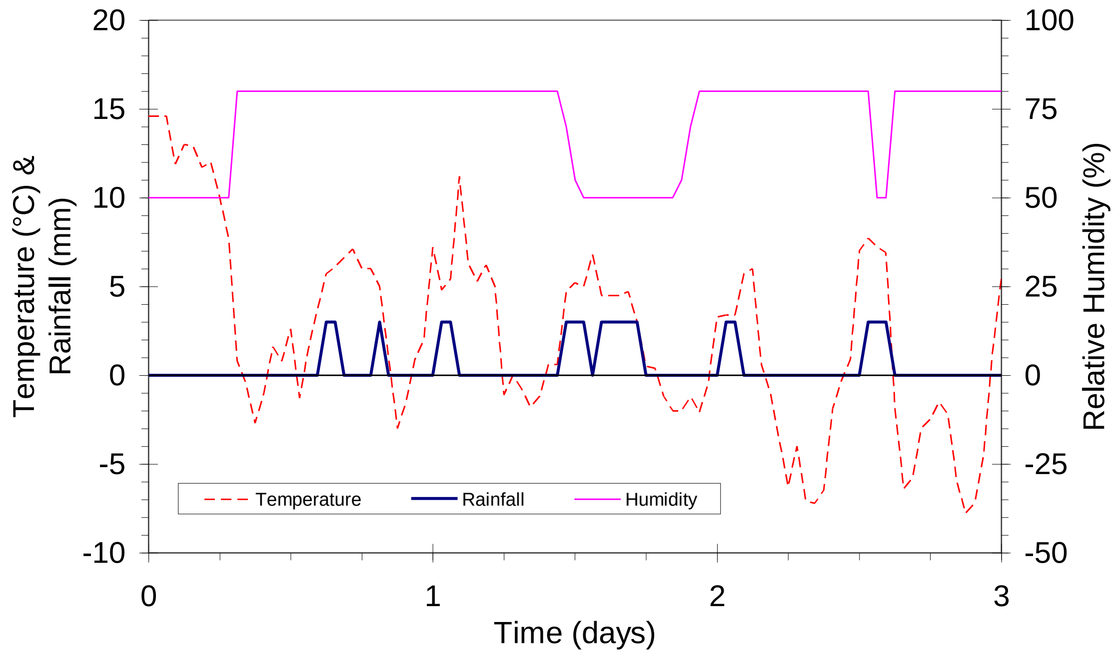

Figure 5. Applied 3 day weather cycle; Climatic simulation chamber

Recording Damage

Damage to materials in the salt crystallisation test was recorded using the percentage weight loss experienced by the sample. Damage to materials exposed in the walls was recorded using a visual logging method carried out every 10 days. The face of each of the replacement stones was subdivided into 250 grid squares. Penetrative damage type is determined by assigning an integer value. For a particular grid square for example, a hairline crack running perpendicular to the face of the stone would be recorded as '1', whereas a crack running parallel to the face which had caused spalling would be denoted by the maximum value of 10 (the material having failed to depths of over 5mm). The percentage damage to a block is obtained from the quotient of the accumulated grid damage and the potential maximum damage. This method differs from that used in EN12371:2001 (BSI 2001) in that the damage rating is by type, with for example hair cracks scoring 2 and delamination scoring 8. Numbers of units displaying each damage type are recorded at cycle 5 and 100. While numerical scales of this type are extremely useful at identifying and quantifying damage types, the sliding scale used in this work enables the tracking of the sequential development of damage with time and provides a useful cross reference to the photographic recording of decay also utilised.

RESULTS

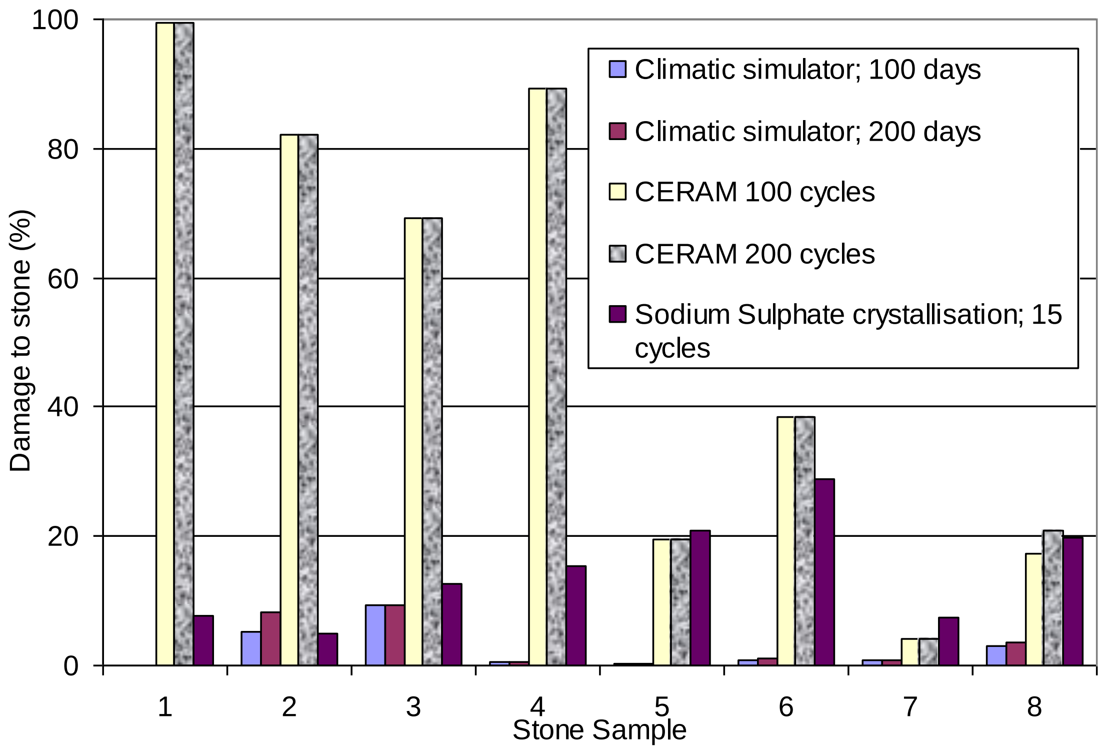

Figure 6 Mean damage to stone for different test apparatus

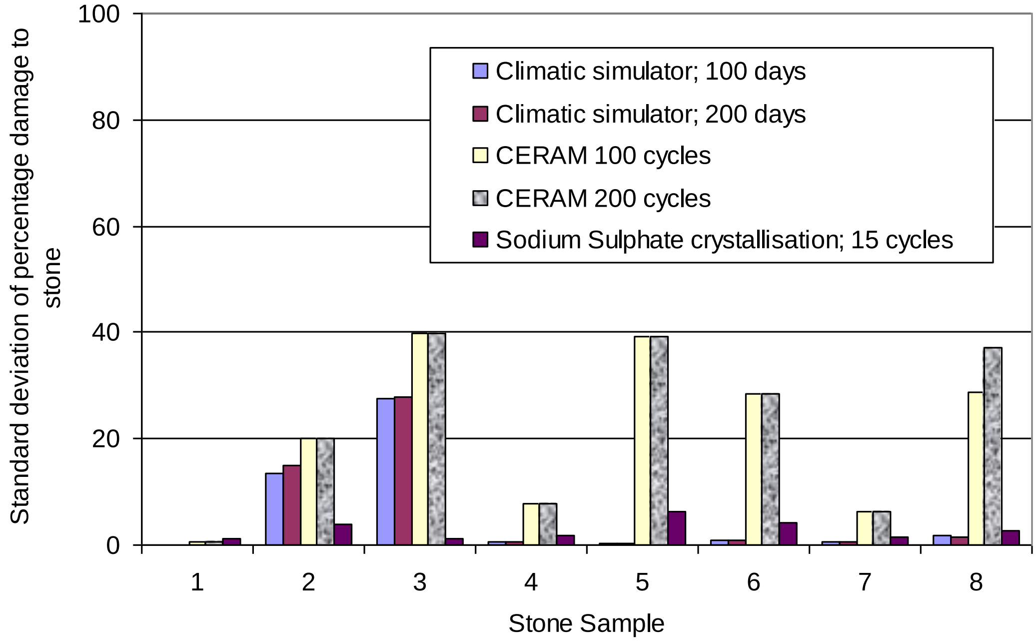

Figure 7 Standard deviation of mean damage to stone for different test apparatus

Figures 6 and 7 compare the overall block damage of the materials in both freeze thaw testing regimes to those of the salt crystallisation test. It can be seen that the CERAM chamber causes significantly more damage than the climatic simulation. Extending the test from 100 to 200 cycles in the CERAM test seems largely unnecessary as little change in both mean and standard deviation of damage occurred.

The CERAM test consistently causes the greatest amount of damage in the materials tested with about half the samples suffering significantly more damage than the salt crystallisation test. Where a high level of damage occurs in the salt crystallisation test, this correlates with similar levels of frost damage in the CERAM test although the standard deviation in the latter is much higher. A high standard deviation (Figure 7) indicates selective weathering and differences in the stone samples within a type which were not evident prior to testing. While this does not conclusively prove the poor durability of the material it may throw doubt onto the performance of a high percentage of the blocks tested and therefore their use in a large restoration project. Testing at full scale enables such differences in performance to be identified.

The original Bath Stone from the Cathedral performed extremely well in the CERAM test, being the second most durable after sample number 7. However, its performance in the other two tests was below average. The stones' performance in the frost tests indicated that the juxtaposition of the Cathedral stones with other potential replacements in this case did not cause noticeably enhanced degradation.

The tests indicate that both samples 5 and 7 show good resistance to frost weathering. Materials such as the Box Stone Cathedral and sample 6 showed a moderate performance, with samples 2 and 3 performing to a lesser extent in the frost tests.

There were some areas of concern in terms of differential performance between test types. For example stones 1 and 4 showed similar performance in the CERAM test, the climatic chamber and in the salt crystallisation test however sample 1 is known to be very durable in practice, while stone 4 has developed a poor reputation for external use.

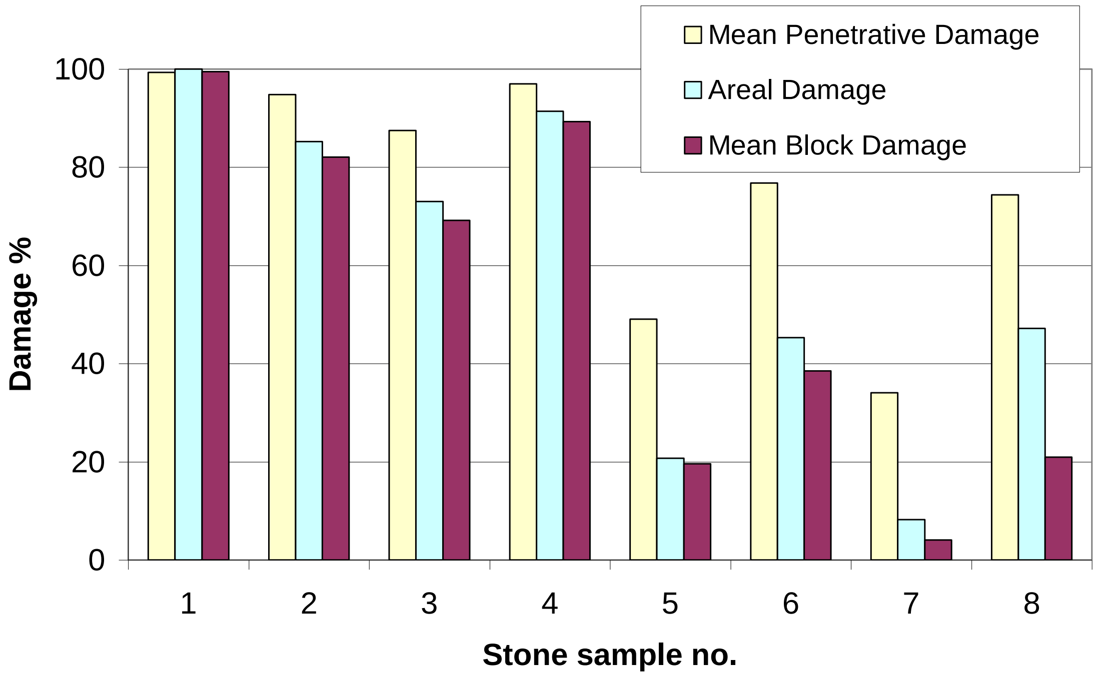

Figure 8 Summary of the lateral extent and penetrative nature of damage generated during testing in CERAM apparatus after 200 cycles

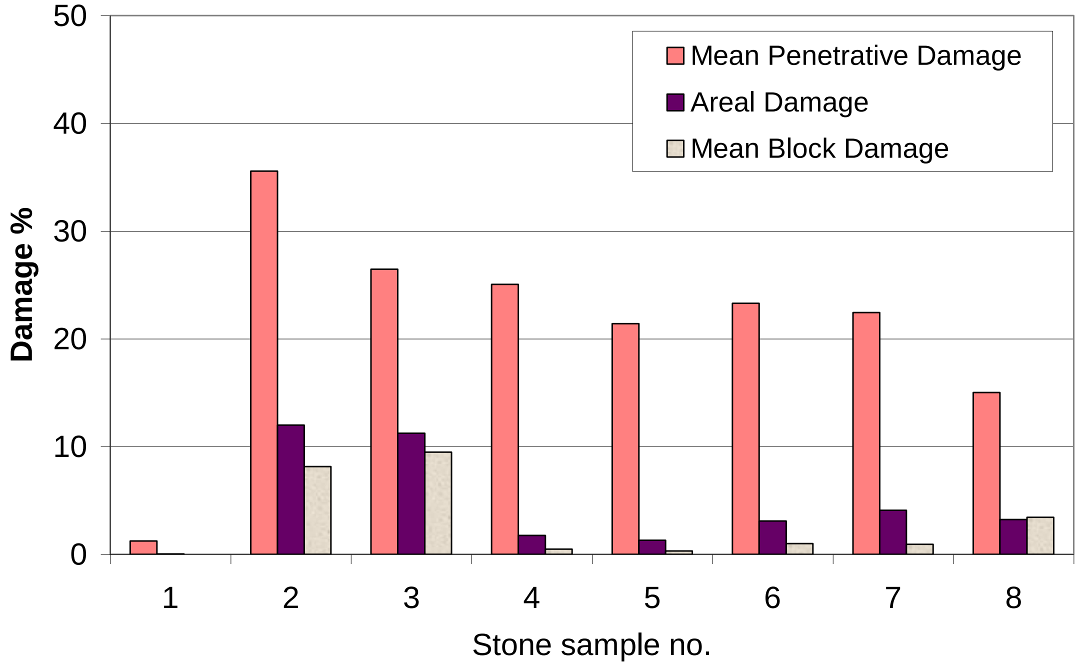

Figure 9. Summary of the lateral extent and penetrative nature of damage generated during testing in Climatic Simulation Chamber after 200 days

Further insight into performance can be gained for frost damage through comparison of the areal extent of damage and mean depth of penetration of the damaged areas. The CERAM test method causes damage which is both widespread and to considerable depth (Figure 8) notably for samples 1 to 4. In comparison, the climatic chamber (Figure 9) causes much less areal damage and generally lower penetrative decay.

The choice of the optimum stone was achieved by comparing the results shown in Figures 4 & 5 and the criteria set by English Heritage. Stone 7 was selected as it has the lowest percentage damage and a low standard deviation over the three tests and was also subject to low areal and penetrative damage in both freeze-thaw tests.

Conclusions

- Test results will depend on the apparatus or method used; some stone samples show similar performance in one or more tests, while other samples show differential performance, sometimes with completely conflicting results.
- Damage, especially areal extent of decay, is considerably reduced in the more realistic conditions of the Climate chamber in comparison with the accelerated test conditions in the CERAM test.
- The CERAM test causes frost shattering of stone, which is an appropriate mechanism of decay, but the exposure conditions are very harsh. The extremes of temperature if experienced in the United Kingdom would be on an irregular basis, and in most locations these conditions would not occur.

- More faith has been put into the climatic simulator. This is due to the more realistic nature of the test and to the observation of minimal damage to the majority of the samples over 200 days of testing.

<u>Recommendations</u>

On this basis of these tests it was suggested that consideration be given to the use of either sample 7 or sample 5 for the restoration work. Sample 1 was considered to be an acceptable stone for use in areas of the cathedral subject to slow freeze thaw cycling, in areas not visible to the public as, aesthetically, it was of somewhat different colour to that of the original stone.

As a result of this research it was decided that Sample 7, the Syerford stone was ultimately the type to be used in the current restoration project (TRURO CATHEDRAL 2005).

Acknowledgements

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Figure Captions

Figure 1. View of Truro Cathedral. (Wikimedia Commons, 2007)
Figure 2. Weathered statue. (Truro Cathedral 2005)
Figure 3. Inspection of test wall in CERAM test chamber
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Figure 6 Mean damage to stone for different test apparatus
Figure 7 Standard deviation of mean damage to stone for different test apparatus
Figure 8 Summary of the lateral extent and penetrative nature of damage generated during testing in CERAM apparatus after 200 cycles
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Table 1

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1	Essentially an oöidal limestone, containing quantities of other materials such as coated grains, stromatoporoids and fragments of shell, echinoids and corals. Oöids are typically about 530 μm in diameter, stromatoporoid fragments as large as 4 mm in length and broken fragments of shell and other organisms can be as small as 150 μm. Compaction of the sediment prior to cementation varies. The cement ranges from microspar to sparite, although the latter tends to predominate. The porosity tends to be confined to micro-porosity in the laminae of the oöids.	A French Jurassic limestone. This appeared to offer a good petrographic match.
2	Sample consists of oöids and other grains in a sparitic matrix. However, many of the oöids, which tend to be between about 800 μm to 900 μm in diameter, have become very diffuse due to micritisation of the laminae. Rounded grains, which range in diameter from about 450 μm to over 2mm, are normally enclosed in a coarse sparitic cement, there are patches of micritic mud containing quantities of fine-grained broken fossils fragments. These patches are up to about 2.5 mm in diameter. The porosity in the stone is largely restricted to micro-porosity in the oöidal laminae, although some macro-porosity occurs where complete spherical grains have disappeared due to solution.	Possibly not aesthetically compatible with the Bath stone in the cathedral, this material has gained a reputation as a good building material.
3	Oöidal limestone, consisting largely of oöids between about 350 μm and 900 μm in diameter. There are also quantities of well-rounded intraclasts of penecontemporaneous sediment, some of which have surface coatings of calcitic laminae, others which are uncoated. Rounded shell fragments range in size from small fragments up to pieces over 2 mm in length. Some of these also have a thin calcitic coating. The oöids and other fragments are in point contact with each other, the cement between them being microsparitic. The crystal size within the spar ranges from about 20 μm up to 700 μm. The macro-porosity is low. However, the micro-porosity, which is largely confined to the oöidal laminae, is high.	The source of this sample has recently been re-opened
4	Sample consists largely of oöids, although appreciable numbers of coated grains also occur. The oöids have diameters between about 300 μm and 900 μm, the coated grains having a slightly larger range of between about 220 μm and 1.3 mm. Occasional fragments of echinoid, up to 950 μm in size are present and, although shell fragments do exist in the sample, they tend to be relatively small and are often recrystallised in the matrix. This cement is micro-sparitic, with individual crystals ranging from about 20 μm to 350 μm in size. Constituent grains tend to be 'floating' in the matrix rather than being in point contact. Porosity is restricted to a micro-porosity in the oöidal laminae, but this is not very great.	This compact close-grained stone is often considered more suitable for interior, rather than exterior use. However, it has been used extensively for exterior ashlar, apparently quite successfully.
5	Poorly sorted stone consisting predominantly of fragments of shell, calcareous algae, intraclasts of contemporaneous sediment, pieces of broken echinoid and with some oöids and coated grains. Grain size is very variable, ranging from less than 500 μm to more than 1.75 mm. The grains tend to be in point contact and the intervening cement is frequently micritic. The porosity of the stone is largely restricted to areas where the nuclei of oöids or coated grains have been lost, or to microporosity in some of the algal coatings on grains.	This is a slightly shelly and harder stone than many Bath stones and has a good reputation for exterior work.

6	Although containing oöids, this stone is a mixture of these particles together with coated grains, fossil fragments, intraclasts and algal masses, none of which are a predominant sediment type. The sediment is also poorly sorted, particles ranging in size from about 130 μm to 2.2 mm. The oöids and coated grains tend to be the smaller components, ranging in diameter from about 480 μm to 800 μm, whereas the intraclasts of penecontemporaneous sediment can be between about 1.3 mm and 2.2 mm in length. Echinoid fragments up to. 1.5 mm in diameter and shell fragments up to 2 mm in length are also present, as are foraminifers. The masses of filamentous calcareous algae can be up to 1.3 mm in diameter. The sediment is relatively well packed although there is no evidence for distortion of the components due to compaction. The cement in the pore spaces between the grains is a mixture of micrite and micro-sparite, the latter appearing to be the result of crystallisation of the former. The porosity is moderate, being a mixture of macro-porosity, where oöids and other particles have been dissolved and micro-porosity in the laminae of the oöids and coated grains.	This is what is often considered a typical and, reportedly, durable, oöidal Bath stone.
7	This is a silicious oöidal limestone. Quartz grains sub-rounded to sub-angular between 90 μm and 260 μm in diameter and concentrated in layers about 1.75 mm thick in the stone, where the they can constitute up to 10% of the rock. Overall concentration of silica about 3.75%. Oöids are between about 300 μm and 1mm in diameter. Echinoid fragments up to about 1.2 mm in diameter and shell fragments well over 3 mm in length have also been noted. The constituent fragments from which the stone is composed are 'floating' in a uniformly crystalline micro-sparitic matrix 85 μm to 175 μm in diameter. The porosity of the stone is low to moderate in the section studied, consisting of a macro-porosity where oöids have been dissolved away, to a micro-porosity related to the oöidal laminae.	Although not a true Bath stone, coming from the Cotswolds east of Cheltenham rather than the Bath area, this stone has favourable petrographic properties and an acceptable appearance.
8 Control	Predominantly oöids with some coated grains, set in a micro- sparitic matrix. The grains range in size from about 350 μm to 1mm, being typically 500 μm to 600 μm in diameter. Oöids micritised and tend to be in point contact with each other. The porosity of the stone is largely a micro-porosity confined to the oöidal material.	Control sample from the North Porch of the Cathedral

Table 1. Petrography of the samples tested. Taken from report to English Heritage

(JEFFERSON 2001)

Table 2

Sample	Average Porosity	Standard Deviation of Porosity	Average Saturation co-efficient	Standard Deviation of Saturation co-efficient
1	14.22	0.64	0.87	0.05
2	12.94	3.76	0.81	0.09
3	27.20	1.92	0.78	0.05
4	21.55	2.82	0.83	0.02
5	24.05	4.34	0.77	0.07
6	24.75	1.59	0.79	0.05
7	27.78	1.45	0.71	0.02
8	30.09	0.60	0.78	0.02

Table 2. Porosity and saturation co-efficient of the samples shown in Table 1. (Method in ROSS & BUTLIN 1992)

Table 3

Ceram Research cycle	Element	Notes
Pre-conditioning	Soak	7 days at +20ºC
	Pre-freeze	6 hours at -15°C
Freeze-thaw cycle	Thaw	20 minutes from -15º to +25ºC
	Rain	2 minutes
	Drain	2 minutes
	Freeze	120 minutes +25ºC to -15°C
	Cycles per day	10

Table 3: Basic CERAM research cycle (PEAKE & FORD 1984)