Deterioration & Weathering Effects on the Engineering Properties of Sydney (Yellow Block) Sandstone when used as a Building Material

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Abstract: Sydney (Yellow Block) Sandstone is the primary building material used in many 19th century buildings in the Sydney, Australia. As a natural material, it is subject to deterioration in the salty environment and in extreme cases will need to be removed and replaced. Two cornice pieces have been removed from the Australian Museum due to evidence of visual decay patterns. Stone samples from within these removed building elements were tested for their engineering properties after over 100 years of natural exposure. The decay patterns on the removed stone would have resulted from sodium sulphate ingress as opposed to sodium chloride. It was also found that the stone has essentially become weaker, softer, and less durable with an increased capacity to absorb water. The degree of exposure experienced by the building element was also found to be a factor in the loss of stone quality.

Keywords: Sandstone; Yellow Block; Sydney Heritage; Dimension Stone; Strength; Durability; Deformability; Water absorption; Salt resistance.

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1. Introduction

Dimension stone, in all places in the world, play an important part in defining the history of a city and its geological surroundings (Frangipane, 2004). The sandstone that dominates the landscape in a 100km radius of Sydney covering an area of approximately 12,500km² is known as the Hawkesbury Sandstone (Image One). According to Spry (2000), there are 6 prominent classifications of Sydney Sandstone drawn primarily from the sandstone’s governing colour and colour change. One classification of this Triassic sandstone, used as dimension stone in Sydney’s 19th century historical buildings, is colloquially known as Yellow Block. It is seen famously as the primary building material in symbolic Victorian buildings such as Sydney Town Hall, Art Gallery of New South Wales and the Queen Victoria Building.

In the turn of the twentieth century, sandstone was believed to have become outdated and unfashionable. Buildings, now considered incredibly precious to Sydney heritage, were considered obsolete and considered for demolition (Fitzgerald, 2002). It was not until the 1970’s when the historical architecture of Sydney was appreciated once more. By this time it was realised that natural stone does not have an infinite life when used as a building material; it is subject to weathering and deterioration in the harsh, aggressive urban Sydney environment. The structural failure of historical masonry structures has not been a problem for Sydney buildings. However, the reliability of historic buildings consisting of low quality sandstone has been compromised in European countries; it has led to the collapse of several historic monuments (Verstryenge et al, 2010).

Due to a shortage in knowledge on the effects weathering has on the engineering properties of Yellow Block when used as a building material, this paper focuses and aims to analyse sandstone removed from one of Sydney’s most prominent historical structures, the Australian Museum. This research’s primary objective is to further understand the reliability of Yellow Block. This is vital information which will help ensure the conservation of these important structures.

The study also briefly discusses the requirements of stone replacement. Stone replacement plays a vital role in maintaining the integrity of the building. According to the ICOMOS Burra Charter, stone conservation requires a cautious approach – ‘changing as much as necessary but as little as possible’. Stone, which is removed from a building, is assessed to have high levels of visual deterioration that are either structurally compromising or aesthetically unsuitable. However, in most cases worldwide, the authentic replacement stone for a building is not available (Quist, 2009). There is a demand for distinctive Yellow Block stone to continue to conserve Sydney’s important heritage structures and history.

Stone used for construction purposes, at the very least, should have good availability, high strength properties (compressive, tensile, high wet/dry ratio), ability to resist salt attack and low porosity. Currently, there are no clear set of engineering property standards for the selection of replacement dimension stone in Australia. NSW Public Works has a set of standards they aspire to but these are not used industry wide. The only collective standards are AS/NZS 4455 & AS/NZS 4456 (Masonry Units and Segmented Pavers), which are by no means adequate. Professionals in the industry make their own assessments upon what is required. As our best sources of Pyrmont sandstone begin to deplete, it poses the question of which stone is most appropriate for stone replacement. Additionally, this research discusses the stone used for replacement in the Australian Museum and its suitability.
2. Experimental Methodology

2.1 Australian Museum

The historical building from where the samples have been obtained is the Australian Museum, College Street. This important piece of neoclassical architecture by James Barnet, completed 1866, was built of Pyrmont Yellow Block (Irving, 2006, p 17) and opened to the public in 1868. The building is listed on the New South Wales State Heritage Register (NSWSHR 2008).

The Australian museum is the oldest institution (founded 1827) in the country and is of great historical, cultural, social and architectural significance. The structure shows an innovative use of sandstone as a material and was an advanced construction for its period. It is a prominent structure in the Sydney landscape and is the most intact piece of nineteenth century architecture today.

2.2 Sampling Approach

The samples were taken from two cornice pieces removed off the Barnet Wing, West Elevation. Cornice Piece One is taken from a middle building element on the elevation and Cornice Piece Two is taken from the left cornice piece (Image Two). There are no records detailing the quality of the stone prior to it being placed in the building, so unfortunately there is nothing indicative of its initial quality. However, it is a reasonable assumption that the original stone would be of similar, if not of greater, quality to stones currently being used for replacement.

A cornice piece was selected as the building element to investigate due to its high levels of exposure to weathering and stress. They represent an extreme example, in essence, a worst case scenario of the weathering to the stone. Cornice stones, are more susceptible to deposits of dry particulate material from pollution; this reacts with acid gases, becomes soluble in rainwater and can then transfer into the stone (Riley & Heiman, 1996). The Sydney city environment is a salty marine environment with moderate levels of pollution through the combustion of fossil fuels and also long periods of rain.

Two cornice pieces have been used for analysis to ensure reliability in the data but also for comparative purposes. When the two cornice pieces were in situ in the building they both experienced different degrees of exposure. The first cornice piece was relatively sheltered with only one side being directly exposed to wind and salt. The second cornice piece was in a much more vulnerable position which a high level of exposure to its surrounding environment. A comparison is made between the two different cornice pieces in terms of their locality in the structure to determine whether direct exposure was a factor in decay.

Image Two: An image of the Australian Museum taken in recent times. The image indicates the location from which Cornice Piece One and Two were extracted from. New stone has replaced the removed building elements. (Photo: McSkimming, 2011)

The two cornice pieces both exhibit the presence of various types of weathering and deterioration patterns. These are (with classification according to Verges-Belmin, 2008); surface degradation, slight
sanding, granular disintegration, contour scaling & flaking, pitting, discolouration, soiling, alga growth and there are missing parts. None of these decay patterns are particular prevalent, however the second cornice piece does have a higher degree of weathering, particularly discolouration. These forms of decay are brought about by natural processes including cyclic wetting-drying, thermal expansion, atmospheric pollution and salt concentration in the Sydney environment. It has also been found that with Sydney Sandstone, stone exposure leads to the progressive decay of the natural consolidant, consisting primarily of clay, which is the cause of some of the deterioration (Friolo et al, 2003).

The samples have been cored and sliced from the internal stone to ensure that the stone has not been exposed to first hand weathering. Whilst the external may be on the verge of disintegration, the internal would be indicative of more intact dimension stone (Image Five). Exposed stone would have reduced strength, cohesion and its surface would be reduced by flaking and disintegration (Dragovich, 2010). It has been concluded that the age of the stone is not a factor for the weathering of sandstone; it does not lose strength with time, but will just deteriorate gradually if exposed to weathering effects (Fitzner, Heinrichs & LaBouchardiere, 2003).

2.3 Engineering Properties for Analysis

Strength: The strength of sandstone is primarily dependant upon its diagenetic bonding and the stone is generally classified by geologists accordingly. Strength testing is required in the dry and wet state; this is because sandstone loses significant strength upon wetting (also known as ‘softening’). There is a distinctive difference between the strength of sandstone in the wet and dry conditions which can be attributed to by its petrography and also for geotechnical reasons.

Hawkesbury sandstone also has been shown to exhibit soil-like behaviour in terms of the application of Terzaghi’s effective stress principle. This is essentially where the effective stress of a soil or rock is equal to the total stress in any direction, minus the pore water pressure (Terzaghi, 1936). The adsorptive pore water pressure can be thought to be the tensile strength of the water in the rock. In a study by Chenevert (1970), he the adsorptive pore water pressure of argillaceous rocks through determining the aqueous vapour pressure of the water in equilibrium with the sandstone. He was able to conclude that the decrease in strength of sandstone after water absorption can be explained by the increase in vapour pressure, which causes the rock to expand, which effectively reduces the effective confining pressure of the stone.

It has been concluded that the Hawkesbury sandstone, in fact, does act like an over-consolidated or dense soil and does provide results supporting the effective stress principle. Pells (1977) confirmed a relationship between the suction of the sandstone and the degree of saturation. However, he also concluded that whilst strength gain upon drying is due to high negative adsorptive pore pressures, it is also contributed to by petrographic composition. It has been argued that the constant wetting and drying of the stone softens the matrix and binds quartz grains together due to clay leaching (Franklin 2000).

When the ratio of wet-dry strength is comparatively high, then the sandstone can be assumed to be of higher durability. This ratio increases up to 1 as durability increases. In a practical sense, sandstone with a higher ratio would be effective in highly salty coastal environments. If the values for the wet and dry condition vary more then about 20%, then this is seen to be as unsound (Hunt, 2008).

Predicting the sandstone strength at different saturations can be difficult. Studies have shown that higher strength sandstones with lower absorption have the greatest strength reductions upon wetting. Weak, porous stones tend to be more difficult to predict (Shakoor & Barefield, 2009).

Uniaxial Compressive Strength (UCS): This has been referred to as the ‘centrepiece’ of rock mechanics testing. It is usually the defining property of the rock and most other properties will be compared to it. However, the UCS of sandstone in a practical sense may not be greatly significant. The stresses in a masonry structure are primarily from the self weight of the blocks themselves. In the 19th century a significant parameter for analysis was the height a prismatic column could be built before
crushing at the base from its own weight. This height was found to be over one mile when using medium strength sandstone. From this it can be deduced that the strength of the stone is not a defining factor in terms of the design of a building. A stone structural element is much more likely to fail by buckling then by crushing (Heyman, 1966).

Therefore, the vertical and lateral loads on ashlar blocks on a heritage structure would not be particularly large. A problem, however, will arise if there is a large dead load on low strength sandstone. However, it is more common for the UCS to be used as a general indicator of the durability of the stone as strong sandstone tends to have a high durability also (Heiman, 2000). The cause for this is that stresses induced by weathering processes brought about by high levels of exposure have to exceed the strength of the material before it can fail. Strength properties, therefore, are also a measure of the grain fabric cohesion and the intensity of its cementation (Stuck et al, 2011).

The stone, when undergoing strength testing, is tested either perpendicular or parallel to the grain. Generally speaking, it is a vital consideration to lay stone with the bedding planes horizontal (Hunt, 2008). This is to avoid splitting of the stone. However, it has been shown with Hawkesbury sandstone that stone tested parallel or perpendicular to the grain usually tend to give similar results for uniaxial compressive strength. It’s only when the specimens are tested on an angle of about 45% to the bedding that the strength can be reduced by factors between 0.2-0.8 (Pells, 1977). For this reason, the stone has only been tested only perpendicular to the grain.

**Tensile strength:** Stone, as material, will have some degree of tensile strength (although considerably lower than compressive strength). Tensile strength will hardly ever be transmitted from one portion of a structure to another. This is due to no tensile strength in the joints (Heyman, 1966). However, for freestanding elements in a structure such as cornice stones, lintels, window sills etc there is requirement for tensile strength. Whilst, in modern day practice, masonry can be reinforced or supported by stainless steel elements, this is not generally the case with dimension stone for heritage structures. Other than structural loading on masonry elements, tensile strength is also required in the stone to resist environmental stresses. These include strong wind actions causing suction on the outer masonry face, vibrations and warping of stone from insufficiently sized slabs (Franklin & Young, 2000). There are several ways to test the tensile strength of stone. The Modulus of Rupture test is utilised in the industry as opposed to the Brazilian Tensile Strength test. The difference being the former tests the bending strength whilst the latter finds the splitting strength.

There is a relationship between the compressive and tensile strength of brittle materials. It was first proposed by Griffith (1921) that fractures occur when the rock energy overcomes the surface energy of the rock. Rock failure is governed for the presence of microcracks in the material. He put forward a stress criterion that predicts an ideal ratio of compressive to tensile strength (known as the Griffith strength ratio) of \( R_G = 8 \). This criterion was later extended by Murrell (1963) who included a third dimension (triaxial stress) in the analysis. He concluded that the ideal ratio of compressive to tensile strength (known as the Murrell strength ratio) is \( R_M = 12 \).

**Water Absorption and Bulk Specific Gravity:** Sandstone erodes and weathers from moisture penetration. Recent investigations at Fort Denison, Sydney, have shown that stone fully submerged and above the tidal line remain intact, whilst the stone at the tidal zone is more eroded, a similar phenomenon seen in timber. This is due to the constant wetting and drying cycle. This example of stone in an extreme environment suggests a need for low absorption.

Water Absorption is dependant upon the porosity and permeability of the stone. The porosity is a measure of the volume of pores in the stone sample whilst the permeability is dependent on the size of the voids and how they are connected. The bulk specific gravity (also known as relative density) is the mass per unit volume with respect to water. This factor is determined when the rock is being compacted and is controlled by the density of the minerals and the porosity of the rock. The extent of burial beneath other deposits and the age of these deposits contribute to the sandstones density (Goodman, 1993, p 87). It is an important parameter as it used when calculating the weight of the dimension stone in situ.
Generally, a stone with low absorption and high density relates to a greater strength. It was shown that rock strength and porosity are related exponentially; strength decreases as porosity increased (Hoshino, 1981). It should be noted that there are exceptions to this rule, it was has been showed that stone with high absorption and low density has high strength if it has a siliceous binder, however this is more relevant to quartz-rich sandstone which is more durable sandstone then Yellow Block (Franklin, 2000).

It has been shown in practice that predicting sandstone strength from density can only really be done in a qualitative manner. When comparing the two parameters from various sources it was found there was a large variance in strength (20-200MPa) with only a small variance in density (2.1-2.6t/m³); thus making it too difficult to accurately make a quantitative prediction due to the large scatter of data (McNally & McQueen, 2000).

A low porosity may also indicate a good durability as it’s less susceptible to salt attack and will act to retard penetration of the salt solution (Warke, Smith, & McKinley, 2004). It has been found that the porous areas of the stone are where the main weathering processes occur (Weishauptova & Prikryl, 2004). However, assuming a stone has high durability due to a low porosity can be dangerous; due to the mineralogy of some stones, it may still be susceptible to attack which is why durability tests must also be conducted.

**Durability – Resistance to Salt Attack:** Sandstones resistance to salt attack is an indication of durability. Dimension stone in the Sydney environment has a high level of salt exposure and the infiltration of salts is usually via the surrounding mortar. This test is mainly used for comparative purposes. Resistance to Salt Attack has been noted to be unrelated to the other physical properties of sandstone (Wallace, 1971), however this is debateable in more recent discussion.

Durability is assessed by cyclic immersion in a sodium sulphate solution where upon the salt crystallises in the stones pores. The weathering effect observed in the stone is a result of the transformation from the water-free thenardite (Na₂SO₄) into a hydrated chemical phase called mirabilite (Na₂SO₄·10H₂O) (Rothert et al, 2005) which results in a dramatic volume increase, approximately of 300% (Price & Brimblecombe, 1994).

According to the Australian standard the test can also be performed using a solution of sodium chloride. The damage patterns brought upon by the sodium chloride are thought to be from the crystallization pressure; the pressures contributed by the hydration process and the crystallization process is greater than the tensile strength of the porous natural stone (Rothert et al, 2005). The Australian standard dictates a more concentrated sodium chloride solution. In European countries it is not uncommon to see the test performed with other salts such as magnesium sulphate and calcium sulphate. The tests done are contextual to the environment in which the stones are located.

Resistance to salt attack was initially used as an accelerated freezing test in the 19th century and only became a means of assessing durability in the 1920s. Standards Australia began compiling a method of testing after the work of Spry in 1983 that provided a correlation between the sodium sulphate test and the stones performance (West 2000).

In a later work Spry (1989) devised a classification system where:

- **A class**: 0-1% mass loss (Very durable)
- **B class**: 1-5% mass loss (Increased susceptibility to salt attack)
- **C class**: 5-10% mass loss (Susceptible to salt attack)
- **D class**: 10-100% mass loss (Non durable)

The rate of drying in the oven influences the hydration state of the sodium sulphate crystals (West, 2000). Consistency in oven drying temperatures is paramount as a slight change in temperature may change the results of the test. Therefore, the classification of the stone from Spry’s conditions should be considered flexible if some of the results are borderline.

**Deformability:** The deformation of a material from axial loading is important in understanding the behaviour of dimension stone. When stress and strain have a linear relationship, the material is
undergoing elastic deformation which is defined by Hooke’s Law. As it begins to undergo plastic deformation, stress and strain are no longer proportional and the material will be deformed permanently. The relationship between stress and strain determines broadly whether a material is brittle or ductile. Stone is considered to be a brittle material as rupture occurs without any visually indicative signs of elongation and lower values of strain (Beer, Johnston & DeWolf, 2006 p 52). It has been found that sandstone deformation generally is not purely elastic. It was concluded that there will be linear-elastic behaviour for only a small portion of the stress-strain curve whilst the rest will represent microcrack propagation (Dyke & Dobereiner, 1991).

In Figure One, the behaviour of three types of sandstone, uniaxial compressive loaded in the dry condition, is demonstrated. The values of stress/strain and the behaviour of these three sandstones have been observed by McNally & McQueen (2000). The specimen can either be loaded in compression or tension; the curve would look essentially the same. All the stones are undoubtedly brittle in nature; the ultimate strength is equal to the breaking strength. The first of which can be considered to be of very high strength (100Mpa), yet very brittle, typically a stone rich in quartz. The second is of high strength (60MPa) while the third is weak and soft (20 MPa). The first sandstone would have a sudden, volatile failure as opposed to the third which yields for a portion of the curve. Dimension stone would generally fall into the second category.

\[ \text{Figure One: An example of the behaviour of three sandstones.} \]

\[ \text{Elastic Modulus} \] This is the ratio of stress over strain. It is considered to be an indication of the stiffness of a material; it’s resistance to elastic deformation, where stiffness increases with greater values of the modulus (Callister, 2007 p 138). In terms of analysis, the Elastic Modulus is relevant in order to find the deflection of structural elements.

\[ \text{Modulus Ratio:} \] This ratio (E/UCS) is indicative for failure behaviour of the stone. With reference to Figure One, higher Modulus ratio values between 500-1000 would be typical of the first sandstone, the second would have values between 200-300 and the first giving a value up to 200 (McNally & McQueen, 2000).

\[ \text{Petrography:} \] Quartz particles make up the majority of fragments in Yellow Block sandstone. There are also amounts of feldspar, mica, rock fragments and clay pellets/aggregates. The matrix or binder is composed of clay minerals, secondary quartz particles, iron carbonate mineral siderite and occasionally iron oxides (Franklin, 2000)

It has been suggested that whilst petrographic studies are useful at predicting durability, they are not a reliable means of predicting geomechanical properties. No petrographic analysis or conclusions will be drawn from this research.
2.4 Testing Details and Procedure

Testing procedures were non-existent in the days when these buildings were erected. Instead, the quality of the stone was at the discretion of the stone mason. It is only recently that engineering tests have become such an important requirement of dimension stone selection. The Standards Australia Association (SAA) prepared a series of draft standards for sandstone testing in the 1980s which were utilised for many years (Heiman, 2000). Often American Society for Testing Materials (ASTM) Standards are utilised in dimension stone testing. Currently in the industry, a mixture of both is utilised and will be specified. In order to make the experimental results comparable to recent data, the tests conducted are the same as ones utilised by NSW Public Works for the last two decades.

Water Absorption, Apparent Porosity and Density were found in accordance with ASTM C97:2000. Cubes (50mm x 50mm x 50mm) were initially dried in an oven at 60°C for 48 hours and then weighed. Immediately after they were immersed in distilled water of 22°C for 48 hours and weighed afterwards. The samples were then placed instantly into a wire basket, suspended in 24°C filtered water. The basket was suspended beneath an electronic balance.

The Compressive strength was determined in accordance with ASTM C170:1990. It should be noted that the 1990 version of the ASTM Compressive Strength test is utilised and not the 2009 version. This is due to the new standard requiring cubic sandstone samples as opposed to cylindrical samples, which will give a higher value.

Specimens were obtained from ten different localities on the cornice piece in order to determine the range of the strength in the cornice piece (Image Three). The cylindrical cores, from each cornice piece, were grinded down to ensure a flat surface and a length of 125mm with a diameter of 50mm. Half of the specimens were tested in the dry and the rest in the saturated condition. They were loaded at 80kN/min until failure.

The secant and tangent modulus was also determined from a wet and dry sample from each cornice piece. This was done using a compressometer which is a system that uses lightly touching screws to measure the deflection of the specimens.

The Modulus of Rupture was tested according to ASTM C90:2009. This consists of a three point loading test which loads the specimens at 1.5kN/min until failure. The specimens were ten rectangular prisms (100mm x 200mm x 60mm) and were tested in the dry and saturated condition.

The resistance to salt attack and also the durability of the stone was found in accordance with AS 4456:10.2003. Cubes (50mm x 50 mm x 50mm) were exposed to 15 cycles of a salt solution, oven-drying and then cooling. The test was undertaken twice; first with a 6.2% sodium sulphate solution and the second with a 14% sodium chloride solution. Each specimen spent two hours immersed in the solution, dried in an oven at 65°C for 20 hours and then cooled in a dessicator for two hours thereafter. The specimens were inspected for visual decay and also weighed; this completed one cycle. The total mass loss of the specimens was determined by filtering and weighing the lost residue.

Image Three: The ten separate localities were cores were obtained from using a diamond drill.
3. Results and Discussion

3.1 Summary

A summary of the test results can be viewed in Table One.

<table>
<thead>
<tr>
<th>Property</th>
<th>Cornice Piece One</th>
<th>Cornice Piece Two</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption (%)</td>
<td>3.94</td>
<td>4.764</td>
</tr>
<tr>
<td>Apparent Porosity (%)</td>
<td>9.145</td>
<td>10.589</td>
</tr>
<tr>
<td>Bulk Specific Gravity (dry) (t/m$^3$)</td>
<td>2.319</td>
<td>2.222</td>
</tr>
<tr>
<td>Bulk Specific Gravity (wet) (t/m$^3$)</td>
<td>2.410</td>
<td>2.331</td>
</tr>
<tr>
<td>Uniaxial Compressive Strength (dry) (MPa)</td>
<td>Range: 50.8 - 60.5</td>
<td>Range: 36.6 – 43.7</td>
</tr>
<tr>
<td>Average</td>
<td>54.8</td>
<td>41</td>
</tr>
<tr>
<td>Uniaxial Compressive Strength (wet) (MPa)</td>
<td>Range: 17.1 - 19.1</td>
<td>Range: 16.7 – 19.9</td>
</tr>
<tr>
<td>Average</td>
<td>17.8</td>
<td>18.1</td>
</tr>
<tr>
<td>Average Wet/Dry Ratio</td>
<td>0.326</td>
<td>0.449</td>
</tr>
<tr>
<td>Deformability (dry)</td>
<td>$E_{tan50}$: 9.2 GPa</td>
<td>$E_{tan50}$: 8.34 GPa</td>
</tr>
<tr>
<td>Modulus Ratio</td>
<td>161</td>
<td>203</td>
</tr>
<tr>
<td>$E_{sec50}$: 5.35 GPa</td>
<td>$E_{sec50}$: 6.29 GPa</td>
<td></td>
</tr>
<tr>
<td>Modulus Ratio</td>
<td>88</td>
<td>143</td>
</tr>
<tr>
<td>Deformability (wet) (GPa/No units)</td>
<td>$E_{tan50}$: 3.21 GPa</td>
<td>$E_{tan50}$: 3.75 GPa</td>
</tr>
<tr>
<td>Modulus Ratio</td>
<td>186</td>
<td>221</td>
</tr>
<tr>
<td>$E_{sec50}$: 1.24 GPa</td>
<td>$E_{sec50}$: 1.76 GPa</td>
<td></td>
</tr>
<tr>
<td>Modulus Ratio</td>
<td>72</td>
<td>104</td>
</tr>
<tr>
<td>Modulus of Rupture (dry) (MPa)</td>
<td>Range: 8.5 – 9.3</td>
<td>Range: 5.8 – 7.1</td>
</tr>
<tr>
<td>Average</td>
<td>8.8</td>
<td>6.5</td>
</tr>
<tr>
<td>Modulus of Rupture (wet) (MPa)</td>
<td>Range: 1.8 – 2.1</td>
<td>Range: 1.8 – 2.4</td>
</tr>
<tr>
<td>Average</td>
<td>1.9</td>
<td>2.1</td>
</tr>
<tr>
<td>Average Wet/Dry Ratio</td>
<td>0.225</td>
<td>0.317</td>
</tr>
<tr>
<td>Resistance to Salt Attack (% mass loss)</td>
<td>Sodium Sulphate: 7.57</td>
<td>Sodium Sulphate: 3.35</td>
</tr>
<tr>
<td></td>
<td>Sodium Chloride: 2.26</td>
<td>Sodium Chloride: 1.10</td>
</tr>
</tbody>
</table>

Table One: A summary of the results from the experimental methodology.

3.2 Investigation of causes associated with decay patterns

The actual state of weathered sandstone in situ on building is due to chemical, physical and biological processes. These mechanisms will overlap one another and lead to the state of visual deterioration (Stuck et al, 2011). The resistance to salt attack test has showed how well the sandstone resists the crystallisation of salt within the pore space which effectively leads to a degree of weathering. This effect is not the sole contributor to weathering effects and the test neglects numerous other factors in this process.

This test is generally used to determine the durability of the stone and in this case, it has also been used to help indicate the decay patterns seen on the stone whilst it was in situ in Sydney’s environment. It was found in a study of Yellow Block removed from Sydney Central Railway station that sulphate particles were the predominant salt in the stone, with chlorides in a lesser concentration (Riley &
Heiman, 1996). However, what the study did not discuss in depth was that decay is not just due to the presence of salt; it is from cycles of changing temperature, wetness, wind movements and also the nature in which the salt behaves. Therefore, the high presence of specific salts within the observed sandstone was not necessarily the cause of its decay.

The decay phenomenon and mass change was observed throughout the test for all the specimens. The apparent decay patterns can be classified into three main categories; detachment, surface defects and crustal formation. Detachment includes any change seen on the rock surface which is characterised by a loss of particles and granular disintegration; this is inclusive of sanding, flaking, scaling, delamination and pitting (see Verges-Belmin, 2008 for description of decay patterns). Surface defects include the presence of cracks and crustal formation refers to efflorescence and sub-efflorescence.

The change in mass was the measured property in the test and was recorded after each subsequent cycle (Figure Two). In the sodium sulphate test, after the first cycle all the specimens had a large mass gain which is a result of salt crystallising within the pores. All specimens lost a large amount of debris within the first two cycles; however this loss was still much less then the mass of the salt crystals. In sequential cycles, the mass of the specimens began to drop slightly, however this was not considerable.

![Figure Two: The change in mass as a percentage at the conclusion of each cycle for the sodium sulphate test.](image)

After the first two cycles all the specimens indicated the presence of efflorescence; poorly bonded salt crystals covered the stone samples and gave them a distinctive white colour. This is brought about by evaporation of the saline water from the sandstone. This decay pattern remained present for the entirety of the test. The stones started to deteriorate further into the test; all specimens showed slight pitting and rounding of the edges due to sanding between cycle six and nine.

The specimens C4 and C6, from Cornice Piece One, were the first to develop cracks which occurred at the conclusion of cycle 12. These formations of crack networks, known as craquele, cover the entire stone piece. This would have been a result of the subflurescence, a decay pattern which defines salt crystals forming in the porous structure of the stone which leads to different types of surface decay. As the test continued, the specimens C5 and 2C5, showed cracks at the conclusion of cycle 13 and specimens 2C4 and 2C6 remain uncracked at the conclusion of the test. After the specimens showed
signs of cracking, they began to lose significant amounts of mass in large pieces; this happened almost immediately. This delamination process continued with each succeeding cycle thereafter.

The visual decay phenomenon were not noticeably different across the two Cornice Pieces, however they differed in intensity (Image Four). In general, Cornice Piece Two performed better in the resistance to the sodium sulphate with an average mass loss of 3.35% which classifies it as having increased susceptibility to salt attack, and Cornice Piece One had an average mass loss of 7.57% which classifies it as being susceptible to salt attack (Spry, 1989). There was quite a large range of different values for mass loss amongst the samples as large amounts of debris lost through delamination is unpredictable and is a result of the heterogeneity of sandstone.

The sodium chloride test began similarly to the sodium sulphate test with the particles experiencing a mass gain, where the salt began to crystallise within the pores. Almost immediately it was evident that the sodium chloride was not as damaging to the stone, as during the initial two stages the stones had very minimal debris loss. The loss of mass from the specimens was a slow and gradual process. The decay patterns seen on the sodium chloride specimens were more limited. There was a much lesser degree of efflorescence noted on the stone; they remained uncoloured throughout the test. This is in indication of the stones lower vulnerability to the salt. The degradation of the stone was mainly through sanding and pitting.

Similarly to the sodium sulphate test, there was not a distinct difference between the visual decay phenomenon across the two specimens. This helps confirm the connection between the two cornice pieces and allows a comparison to be more accurate. It was observed, however, throughout the test that the stone from Cornice Piece One was losing considerably larger amounts of mass, which was observed at the bottom of the beaker at the conclusion of each cycle. Both Cornice Pieces had a mass loss in the range of 1-5% which classifies the stone as having increased susceptibility to salt attack (Spry, 1989), however they fall into the lower part of the category and almost are considered to be very durable. Cornice Piece One had an average mass loss of 2.26% and Cornice Piece Two was slightly less with 1.10% mass loss. There is a much smaller range of mass loss results as opposed to the sodium sulphate test. Flaking is a lot of more uniform, gradual and predictable degradation pattern as opposed to delamination.
Cornice Piece Two has proved to be of higher durability with regard to exposure to sodium chloride. As it is seen in Figure Three, the Cornice Pieces initially behave alike with a mass gain from salt crystallisation. As the test proceeds the mass loss from Cornice Piece One specimens becomes greater then the weight of the salt in the pore space. Cornice Piece Two continues to have small amounts of salt crystallise within the pores with little mass loss accompanying it. It is observable in Image 20 that both stones look, for the most part, unaffected by the test. The slight pitting and rounding of the edges is still noticeable.

The different type of decay patterns observed on the stone has been found to be related to the drying rates of the stones and consequently the pore space distribution of thee stones (Ruedrich & Siegesmund, 2007). If the drying rate is fast, sanding will be the dominant deterioration, whilst if the drying rate is slow then flaking is the prevalent decay form. Sanding and flaking are both detachment type decay; flaking is granular disintegration where centimetre sized particles peel off parallel to the
stone surface whilst sanding is similar but of much smaller particles (millimetre or less). During both tests, the stones exhibited sanding, as opposed to flaking. This suggests a fast drying rate of the stone.

There are limitations to this test. Firstly, there are many other factors that may contribute to decay and are not observed, such as temperature and humidity. However, controlling these factors would become more relevant in extreme temperatures and humidity; Sydney’s environment is not significantly different to the controlled conditions used in the laboratory. Secondly, the only measured property of the sandstone after salt exposure was weight loss and observed changes to the stone. Other properties such as change to density, porosity, strength and chemical composition were not observed. Whilst much research and testing has been done using this type of artificial salt exposure and it is an accepted form of measuring stone durability, observing the nature and rate of the sandstone breakdown does not readily identify the precise weathering mechanisms or rock properties that control its response (Turkington & Paradise, 2005).

The nature and rate of sandstone breakdown has been observed with its exposure to sodium sulphate and sodium chloride. Cornice Piece One was proven to be of high vulnerability to both salt solutions. The sandstone responds substantially more strongly to sodium sulphate than to sodium chloride. It is evident from this test that the sandstone is more highly susceptible to sodium sulphate attack. The volume increase brought upon by the transition of the sodium sulphate to its hydrated chemical phase proves to be more detrimental than the crystallization pressure of the sodium chloride, even though the sodium chloride solution was of a higher concentration.

There is some room for error throughout the process of this test. The basis of salt resistance test was measuring mass loss. However, the mass loss (%) will always be lower then the actual loss of mass. As the specimens began to show signs of granular disintegration, which is first seen in the form of sanding, there is a loss of matter. It was not possible to ensure that all lost particles were obtained in the beakers; mass was lost in transit. For instance, when moving the specimens from the drying racks, to the oven, to the set of scales small amounts of matter were lost. This was seen in extremities towards the end of the sodium sulphate test; the specimens become very frail and greater amounts of particle loss are evident in transit. It was also observed that during the process of sieving the remaining sandstone residue, small amounts would, in some occasions, escape through the sieve. The total loss of mass that was unable to be recorded would have been relatively small and would not have altered the results extensively. The results for this test are therefore considered to be conservative.

### 3.3 Weathering effects on Physical Properties

After 100 years of natural exposure as a building element, a number of physical property tests were done to determine whether the integrity of the stone has been compromised. The first test conducted, ASTM C97, gave results for water absorption, porosity and bulk specific density. The results from ASTM C97 had high reliability; the results differed by less than 1% across the samples from the same cornice piece. There were very little sources of error within this test except that the scales used when measuring the mass of the specimens submerged in water was not sufficient. The apparatus only allowed the sandstone mass to be recorded to one decimal, as opposed to two which is outlined in the code.

The specimens obtained from Cornice Piece One demonstrated more superior results with an average absorption of 3.94%, apparent porosity of 9.145% and dry and wet bulk specific gravity of 2.319t/m$^3$ and 2.410t/m$^3$ respectively. Cornice Piece Two performed with an average absorption of 4.764%, apparent porosity of 10.589% and dry and wet bulk specific gravity of 2.222t/m$^3$ and 2.331t/m$^3$ respectively. These values, especially for Cornice Piece Two, are considered to be inferior for Sydney’s dimension stone.

It is evident that the porosity of the stone has increased with time and has effectively increased the capacity for the stone to absorb water. The density values are not particular low; small material loss over time has not been a notable factor for a decrease in density. However, as the scatter of typical results of Yellow Block for density is very small, it’s more difficult to observe a change in the density.
In the ASTM C170 test, the dry and wet uniaxial compressive strength of the specimens were found. The corresponding elastic modulus was also determined. The Uniaxial Compressive test utilised specimens from 10 different localities on each cornice piece; this gave an indication of the spread of strength throughout the stone element. The samples all failed in shear. Cornice Piece One had a mean dry strength of 54.8 MPa, which was of a much higher standard to Cornice Piece Two which gave a mean dry strength of 40.5MPa. Granular disintegration due to different forms of weathering would lead to a loss of cohesion within the stone. Weathering and leaching would also have meant a loss a clay binder from this stone. This would have decreased the strength.

Regardless of testing weathered or fresh stone the range of strength values is expected to differ, to some degree, amongst samples. Nevertheless, the range of dry strength values from Cornice Piece One was substantially greater than the range from Cornice Piece Two. Cornice Piece One had a sample standard deviation of 4.00 and Cornice Piece Two gave a sample standard deviation of 2.60, which proved to significantly different. The fraction of the variances gave a value of 2.37, which allows us to assume unequal variances in the data. Figure Four shows the range and mean of the dry strength from both of the Cornice Pieces.

The result of both the mean and standard deviations of the dry strength from both the Cornice Pieces can be contributed to exposure and weathering and therefore the location of the stone in the structure. Cornice Piece Two has shown a considerable decrease in dry strength, which is fairly consistent throughout the stone. Cornice Piece One, however, retains a high level of dry strength but also shows a much wider range of values. Due to the sheltered position of the first Cornice Piece, areas of the stone have retained possibly the original strength of the stone (max value of 60.5MPa). Other areas, however, of the stone have shown the effects of strength loss from weathering. Cornice Piece two, which has been highly exposed, has lost a large degree of strength uniformly.

![Figure Four: A box plot representing the spread of the results from the dry strength of the two cornice pieces. The top and bottom of the box represents the 75th percentile and the 25th percentile respectively.](image)

The deformations of the sandstone were determined for a wet and dry specimen from each of the Cornice Pieces. The results lack reliability as limited data was obtained; therefore a comparison between the two sandstones would not be accurate. Instead, an analysis of the deformation
Deterioration & Weathering Effects on the Engineering Properties of Sydney (Yellow Block) Sandstone when used as a building Material - Emily McSkimming

characteristics of the sandstone in general and how they have been affected by weathering would be more appropriate.

The Yellow Block showed a relatively typical stress-strain curve indicative of Type III curve (Deere & Miller, 1966) which shows a plastic deformation at the start followed by a linear portion of the graph. For this reason, the tangent modulus appears to give results with higher clarity; the sandstone all had a linear portion at 50% in their stress-strain diagrams which can be observed in Figure Five.

The Yellow Block showed a relatively typical stress-strain curve indicative of Type III curve (Deere & Miller, 1966) which shows a plastic deformation at the start followed by a linear portion of the graph. For this reason, the tangent modulus appears to give results with higher clarity; the sandstone all had a linear portion at 50% in their stress-strain diagrams which can be observed in Figure Five.

![Figure Five: The stress-strain relationship observed in the wet condition of Cornice Piece Two.](image)

The tangent and secant Young’s moduli \( (E_{50\%}, E_{550}) \) were calculated from the stress–strain curves at 50% of wet and dry UCS specimens. The tangent and secant elastic modulus for the dry condition was determined to be 8.34-9.2 GPa and 5.35-6.29 GPa respectively. The wet condition gave values for the tangent and secant modulus as 3.21-3.75 GPa and 1.24-1.76 GPa respectively. According to the classification system in Figure Six (Deere & Miller, 1966) (Prikryl & Stastna, 2010), the sandstone in the wet condition is of low strength with high yielding and in the dry it is of high strength with yielding. The tangent Young’s moduli all gave considerably higher results.

![Figure Six: Classification of the studied sandstone on the Deere-Miller Diagram (Deere & Miller, 1966) with a slight change in boundaries (Prikryl & Statstna, 2010).](image)

The values obtained for the modulus ratio of the stone is considered to be relatively low. Most unweathered Sydney basin sandstones would have a modulus ratio between approximately 200-300 and
weathered stone would be between approximately 100-200 (McNally & McQueen, 2000). Dimension stone is expected to perform with a modulus ratio more towards 300. The obtained modulus ratios were between 161-221. Unweathered sandstone of this quality would be expected to be a lot stiffer with a more brittle fracture. However, it can be thought that the weathering has lead to a much higher yielding and effectively softer stone.

The elastic modulus was determined used a compressometer generally used for concrete. Screws are placed at the top and base of the specimen to measure the deformation. New screws needed to be prepared as the current screws had a too larger diameter to obtain a sensitive result. It was observed, however, that the points of screws may be too hard for the softness of the cylinders in the wet condition. The wet sandstone, due to its high yielding and softness, may not have been able to withhold the intrusion of the screws and could have altered the results slightly.

The Modulus of Rupture Test, ASTM C90, tested the flexural strength of the stone. Due to constraints in obtaining specimens, the specimens are all from the same slice of cornice piece and in effect the same location of the stone. The disadvantage of this is that it does not allow us to gain an understanding of the greater range of strength differing throughout the stone as demonstrated with the UCS test. Cornice Piece One performed to a great deal higher standard with an average dry tensile strength of 8.8 MPa in comparison to Cornice Piece Two which gave an average of 6.5 MPa. When comparing the ratios of compressive strength to tensile strength Cornice Piece One produces a ratio of 6.2 and Cornice Piece Two produces a ratio of 6.3. This deviates from the ideal Griffith Ratio of 8 and Murrel Ratio of 12. This can indicate a greater decrease and degradation of compressive strength in comparison to tensile strength.

The compressive wet strengths from both the Cornice Pieces were the almost identical; Cornice Piece One gave an average compressive wet strength 17.8 MPa and Cornice Piece Two gave an average compressive wet strength of 18.1 MPa. Similar results were seen between the tensile strengths of the Cornice Pieces; Cornice Piece One had an average tensile wet strength of 1.9 MPa and Cornice Piece Two had an average tensile wet strength of 2.1 MPa. In comparison to the dry strengths of the stone, the wet strengths have both decreased dramatically. The wet/dry ratios of the stone are therefore considerably low, with the compressive ratios performing better. Cornice Piece One gave a ratio of 0.225-0.326 and Cornice Piece Two gave a slightly higher ratio of 0.317-0.449.

It was assumed that Cornice Piece One and Two were of similar composition and quality to begin with. Test results, however, have shown that while the stones behaved similarly it is likely that there would have been slight differences in the composition of the stone. As discussed, stone from the same quarry can still be remarkable different. The almost identical wet strength and higher wet/dry ratio seen in Cornice Piece Two show that the stone in this Cornice Piece was of slightly higher quality to begin with. It is suggested that Cornice Piece Two would have had a higher initial wet strength, most likely due to a greater degree of secondary quartz overgrowth. However, without an investigation of the petrographic composition of the stone, this is still uncertain.

### 3.4 Relationships amongst Properties

Making predictions of one property of stone off another isn’t always reliable; the composition of the stone can easily change assumptions. Numerous known relationships between sandstone were witnessed in this research. There was a connection evident between absorption and strength. Cornice Piece Two had a greater absorption/porosity and lower density. It is expected for a high absorption and low density to result in lower strength. Further, if one these properties were to be effected by weathering; a decrease in the quality of the other would follow.

The durability of the stone (measured through resistance to salt attack) is thought to be indicated by the wet/dry ratio, strength value and adsorption. It was found that the wet/dry ratio was in fact indicative of the durability of the stone. Cornice Piece Two, with a greater wet/dry ratio, had greater resistance to the decay brought upon by exposure to sodium sulphate and sodium chloride. The high strength
demonstrated by Cornice Piece One did not prove to be suggestive of its durability; as it readily lost mass from salt attack.

It was also not shown that high absorption lead to lower durability. Whilst it may seem like a greater amount of water absorbed by the stone would prove to increase the amount of salt able to crystallise within the pores, this is not necessarily the case. However, as shown by numerous studies (e.g. Stuck et al, 2011; Snethlage & Wendler, 1996), porosity and pore size distribution control the transportation of the solute. More testing, such as mercury porosimetry, would help clarify the distribution and size of the pores. Cornice Piece One may have had a lower adsorption and porosity; however larger pores would be more detrimental for salt crystallisation.

It has been documented that stone extracted from deeper in the stone, shows a chemical change from weathering and is also more pale yellow in colour (Friolo et al, 2003). It was found, very broadly, that the second cornice piece, which was generally of a much deeper yellow colour, had a lower strength than the first cornice piece. However, no direct relationship was found, nor did this prove to be an accurate measure of predicting the stones strength. It was found that the colour of the stone gave little indication of the strength of the stone; a deeper yellow, due to the oxidation of iron carbonate siderite, was not found to directly decrease the strength of the stone.

### 3.5 Analysis of Long-Term Performance of Stone

NSW Public Works has guidelines for the selection of replacement stone. These guidelines outline desired stone properties and set a minimum value for the application of sandstone as dimension stone. The NSW Public Works standard for the replacement stones used in the building is documented in Table Two. It is noted that this standard is specifically used by NSW Public Works and not collectively within the industry.

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard</th>
<th>Cornice Piece One</th>
<th>Cornice Piece Two</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption (%)</td>
<td>4.1 (max)</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Apparent Porosity (%)</td>
<td>10 (max)</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Bulk Specific Gravity (dry) (t/m³)</td>
<td>2.28 (min)</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Bulk Specific Gravity (wet) (t/m³)</td>
<td>2.38 (min)</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Uniaxial Compressive Strength (dry) (MPa)</td>
<td>50 (min)</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Uniaxial Compressive Strength (wet) (MPa)</td>
<td>25 (min)</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Average Wet/Dry Ratio</td>
<td>0.6 (min)</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Modulus of Rupture (dry) (MPa)</td>
<td>6 (min)</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Modulus of Rupture (wet) (MPa)</td>
<td>4 (min)</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Average Wet/Dry Ratio</td>
<td>0.6</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Resistance to Sodium Sulphate (% mass loss)</td>
<td>1 (max)</td>
<td>N</td>
<td>N</td>
</tr>
</tbody>
</table>

*Table Two: The general requirements for replacement dimension stone as outlined by NSW Public Works in comparison to the results obtained from the Two Cornice Pieces.*
Both Cornice Piece One and Cornice Piece Two do not meet the outlined requirements. Cornice Piece One reaches the majority of the required standards, but does not meet the more crucial demands of the stone. Whilst it retains an acceptable absorption, porosity, density and dry compressive and tensile strength it shows very poor durability. Its wet/dry ratio, due to a dangerously low wet strength, is less than half of what is required.

Cornice Piece Two does not meet any of the standards (except for the dry tensile strength). The effects of weathering have substantially damaged the engineering properties of the stone. It is interesting to note that the stone had a higher wet/dry ratio and a better durability performance. This performance was by no means adequate but it suggests Cornice Piece Two was of higher standard to begin with.

3.6 Suitability of Replacement Stone

A stone selected for stone replacement is generally assessed for its physical, petrographic and aesthetic quality (see Chapter 4). Due to the significance surrounding the colour and oxidising properties of Yellow Block, the aesthetic quality can at times become the main priority in the selection process. However, this should not be the case and the physical and petrographical properties take precedence.

It has been noted that any new materials placed in a building must have similar mechanical properties to the original material, as not to degrade the state of the structure (Quist, 2009). A stone with varying properties could cause numerous problems; instability and weak areas in the structure and permeable locations susceptible to the accumulation of water and possible salt ingress. It was noted in a case study by Quist that an incompatible new stone placed in a structure can be detrimental. Whilst the new stone was concluded to be resistant to salt attack, the different pore sizes and pore size distribution resulted in an unpredictable behaviour of moisture ingress, drying behaviour and salt crystallisation. Therefore it was concluded that in terms of stone replacement a ‘sound balance’ should be maintained between choosing a stone that is ‘authentic as possible’ and as ‘durable as possible’. Replacement stone as similar to the original stone as possible is ensured to be of higher performance. Naturally this is not always possible and compromises need to be made.

It has been noted that approximately 5-10% of the natural stone previously used in buildings is available in most developed countries (Torok & Prikryl, 2010). Therefore, each building requires an assessment prior to choosing a suitable stone replacement. Different structures will have different needs. The McCaffreys stone was used as a replacement stone in the Australian Museum and was considered to be a suitable replacement due to its authenticity, which was a factor of its geology and high quality.
Barnett wing of the building disrupts the orientation of the building as an entirety. This is, nevertheless, an opinion and the article failed to discuss the suitability of the stone from an engineering perspective.

Image 21: The replacement stone in the position where Cornice Piece One was extracted.

An alternative to the McCaffrey’s stone was the Piles Creek ‘Guinea Gold’ Sandstone, quarried near Gosford. It is self-oxidising argillaceous sandstone which is readily available and has been used for restoration work on important buildings such as Town Hall and St Marys. A summary of its physical properties are also summarised in Table Three (Gosford Quarries, 2011).

<table>
<thead>
<tr>
<th></th>
<th>McCaffreys (First Bed)</th>
<th>McCaffreys (Second Bed)</th>
<th>Piles Creek</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption (%)</td>
<td>4.26</td>
<td>4.82</td>
<td>4.2</td>
</tr>
<tr>
<td>Apparent Porosity (%)</td>
<td>9.80</td>
<td>10.83</td>
<td>-</td>
</tr>
<tr>
<td>Bulk Specific Gravity (dry) (t/m³)</td>
<td>2.3</td>
<td>2.25</td>
<td>2.25</td>
</tr>
<tr>
<td>Bulk Specific Gravity (wet) (t/m³)</td>
<td>2.4</td>
<td>2.36</td>
<td>-</td>
</tr>
<tr>
<td>Uniaxial Compressive Strength (dry) (MPa)</td>
<td>45.3</td>
<td>56.5</td>
<td>59</td>
</tr>
<tr>
<td>Uniaxial Compressive Strength (wet) (MPa)</td>
<td>21.7</td>
<td>30.2</td>
<td>30</td>
</tr>
<tr>
<td>Average Wet/Dry Ratio</td>
<td>0.479</td>
<td>0.535</td>
<td>0.509</td>
</tr>
<tr>
<td>Modulus of Rupture (dry) (MPa)</td>
<td>6.7</td>
<td>6.9</td>
<td>9.1</td>
</tr>
<tr>
<td>Modulus of Rupture (wet) (MPa)</td>
<td>2.5</td>
<td>3.6</td>
<td>3.5</td>
</tr>
<tr>
<td>Average Wet/Dry Ratio</td>
<td>0.377</td>
<td>0.524</td>
<td>0.385</td>
</tr>
<tr>
<td>Resistance to Sodium Sulphate (% mass loss)</td>
<td>0.23</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table Three: A summary of the properties of the two lifts of the McCaffreys Stone and of Piles Creek stone.

The McCaffreys (Second Bed) and Piles Creek have similar physical properties. Piles Creek has superiority in most respects, except for its wet/dry ratio in tension which is considered very low. A low wet tensile strength could be brought about by not enough secondary quartz overgrowth to counteract the large amounts of clay in the product (Franklin, 2000). Petrographic analysis would help clarify this matter and a resistance to salt attack would be also helpful. Gosford Quarries doesn’t supply a result for the salt resistance of the stone, which gives the buyer little indication of the stone’s durability.

The McCaffreys stone has very high durability and good resistance to salt attack. It also has a greater wet/dry ratio than the Piles Creek stone. The McCaffreys stone, therefore, reaches the criteria for stone replacement, in terms of engineering properties more sufficiently. It can be considered the more durable stone, due to a lack of data provided on the Piles Creek stone and also seen through a higher
wet/dry ratio. It is also considered more authentic than the Piles Creek stone due to the quarry’s locality.

Further, the properties of the McCaffreys stone are not noticeably different to the stone samples removed from the structure of the museum. It is not expected for the stone to act adversely in the building due to the similarities in properties.

4. Conclusions

Weathering effects have damaged the integrity of the engineering properties of the removed sandstone from the Australian Museum. Both stones have essentially become weaker, of greater yielding, less durable and more porous. The position of the stone in the building, and its level of exposure, has proved to be a factor in the stone’s long-term performance. However, Cornice Piece One, a sheltered building element, performed to a higher standard. Cornice Piece Two, extracted from a more vulnerable location on the building, has not retained as much quality.

Cornice Piece One still reaches the standard for dimension stone replacement in terms of its absorption, porosity, density and dry compressive and tensile strength. Cornice Piece Two does not meet any of the requirements for stone replacement, except for dry tensile strength. The ratio of compressive to tensile strength showed a possible greater degradation of compressive strength to tensile strength. Both stones had similar deformation properties which showed a softer and higher yielding stone than expected of a non-weathered stone. It was shown that Cornice Piece One had a significantly greater range of strength results which shows that some parts of the stone have retained strength, whilst Cornice Piece Two has lost strength uniformly.

Both stones produced dangerously low wet strength values and thus low wet/dry ratios with Cornice Piece Two performing better in this component of quality testing. It was evident from the results, that the two stones had different properties to begin. It can be concluded, however, that Cornice Piece Two had the more desirable and durable properties initially. It has a lower wet/dry ratio suggesting that whilst it has lost significant amounts of clay binder in leaching, it had a greater amount of secondary quartz overgrowth to begin with. Further testing would be required to confirm this and no petrographic conclusions can be made from this research.

The stone performed unfavourable in the resistance to salt attack which is an indicator of stone durability. However, considering the length of time already exposed to salt ingress, this was expected. The durability test has showed sandstone that would already have had large amounts of salt within the pores. Its mass loss was too great for the stone to be considered fresh samples. However, most interesting to note was the instantaneous failure mechanism of the stone after exposure to the sodium sulphate solution. In a practical sense this is a very dangerous deterioration phenomenon. As opposed to a gradual crumbling or wearing away of the stone, the appearance of cracking was instantaneous. It is therefore something to be considered when investigating Yellow Block sandstone in situ; cracking may potentially lead to an onset of rapid deterioration.

Cornice Piece Two had a much smaller mass loss as opposed to Cornice Piece One in exposure to both sodium sulphate and sodium chloride. It was determined that both stones performed more satisfactorily in the sodium chloride solution with a smaller amount of mass loss. It can be concluded that decay effects evident on the removed stone from the Museum would have been more likely to have come from sodium sulphate ingress as opposed to sodium chloride.

Further, it can also be concluded that a higher wet/dry ratio is a very good indicator of the stone’s durability. This exacerbates the importance of ensuring a high wet/dry ratio when assessing the quality of dimension stone and then confirming that result with the resistance to sodium sulphate exposure test. The sodium chloride test, whilst the AS4456 code allows for it, should never be used in isolation when assessing stone durability.
The McCaffreys stone used as the replacement stone in the Australian Museum, although has received harsh criticism in the industry for aesthetic reasons, was a satisfactory selection for the replacement dimension stone on the structure. Sufficient laboratory testing on this stone has showed that it is of high durability with engineering properties that would not be disruptive to the stone currently in the structure.

9. Recommendations

This research has given insight into the long term performance of yellow block stone. In order to continue developing an understanding of the reliability of the stone, similar research should be continued where removed dimension stone is tested for its mechanical properties. This will lead to the development of a model which will allow people in the industry to more accurately predict the strength loss and overall performance of stone in situ on a building.

As the UCS test is the most indicative physical test of the stone’s integrity and also the most time and cost efficient, it would be ideal to core a few cylinders from removed building elements. If this were tested in the wet and the dry then an understanding of the durability of the stone could also be determined.

Further, there is a significant lack of data of the long term performance of Yellow Block stones in the industry. If UCS tests were done when a building undergoes stone replacement, then our understanding of the weathering of stone could be more greatly understood. It is recommended that an index be kept documenting these results as a reference for stone replacers. The tests done to sandstone prior to it being used for restoration only show an indication of short term effects of the stone. This documentation procedure would allow the industry to further understand the long term effects.

In terms of Yellow Block stone replacement, particular attention should be given to freestanding building elements with a greater amount of exposure to its surrounds. It is seen that weathering affects their physical integrity to a higher degree, with particular concern being the wet strength and durability of the stone. If a stone is highly weathered, it should be inspected for cracking as this can lead to rapid deterioration of the stone.

Acknowledgements

This research would never have commenced without the help of NSW Public Works who supplied stone samples, technical documents and relevant, informative advice.

The testing procedures outlined in this report at times were challenging and difficult to achieve in terms of apparatus problems. Thanks to the Jimmy Baxter and the UNSW Technical experts the experiments could never have taken place.

A final mention to Dr Rajah Gnanendran who provided support throughout the course of the year in which this research was conducted.
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