Durability assessment of Hawkesbury Sandstone for use as a foreshore revetment for the Barangaroo Headland Park development in Sydney

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ABSTRACT

A new park facility is under construction on the Harbour foreshore near Sydney's CBD. The park aims to re-create the former natural shoreline, and will provide an iconic venue for leisure and cultural activities. The architectural design of the park required a sandstone block foreshore that matches existing sandstone outcrops throughout the harbour areas. The sandstone used to construct the foreshore is site-won Hawkesbury Sandstone extracted from an excavation near the centre of the site. This paper presents a summary of the approach used by the geotechnical team to advise the main contractor on the quality of the quarried sandstone. The assessments formed part of a quality control process specifically developed for the sandstone blocks. The use of simple field and laboratory tests is described and the site-specific correlations developed for intact rock strength are presented. The findings from durability testing, as well as historical information on sandstone use in marine environments in the Sydney area, are also discussed.

Keywords: geotechnical testing, durability, sandstone, quality control, classification

1 INTRODUCTION

In September 2012, construction work began on the development of the Barangaroo Headland Park at the site of the former container wharves on the Sydney Harbour foreshore west of Sydney's CBD. The project entails construction of a 6 hectare, naturalistic park that aims to re-create the former natural headland shoreline around The Rocks area of Sydney. The design of the park includes two key architectural features: (i) a large, enclosed Cultural Space bounded by an existing sandstone vertical cutting (landward side) and a new counterfort wall structure (seaward side), inclusive of two basement car parking levels; and (ii) a foreshore constructed of rectangular sandstone blocks arranged in a stepped manner to form a graded slope. A site location plan is shown below.

The architectural design of the foreshore revetment required that sandstone be employed, ideally matching the Hawkesbury Sandstone formation that is exposed on the headlands around much of Sydney. Indeed, the project site is underlain by Hawkesbury Sandstone, and it is also exposed along the historic, vertical cutting that defines the eastern boundary of the project site. There was thus opportunity for the main contractor to use site-won Hawkesbury Sandstone extracted from the Cultural Space excavation.

Figure 1. Site location plan

The park development, including the foreshore, has a design life of 100 years. This requirement raised some concerns as to the use of sandstone rock, specifically, as a foreshore revetment in a marine environment. Although there are a number of historical, harbour-facing seawalls constucted of sandstone around Sydney's harbour that are still in reasonably good shape, there is a lack of in-depth study on the general durability of sandstone (and in particular Hawkesbury Sandstone) in a marine foreshore environment.

In view of the above, a project-specific sandstone block quality specification was developed by the contractor with the support of the geotechnical advisor team that aimed to provide a practical means of assessing the likely long-term durability of the sandstone blocks. This paper describes the process adopted for this purpose during construction and the test methods and index parameters employed to derive a quality control block classification, or grading, in terms of optimum placement along the foreshore.

2 SANDSTONE BLOCK REQUIREMENTS AND SPECIFICATION

2.1 Sandstone Block Requirements

The sandstone block foreshore was designed using 3D modelling software, with each block individually assigned an identification number. The typical block dimensions and numbers obtained from the excavation works and subsequent processing are as indicated in Table 1 below.

Table 1: Typical sandstone block dimensions and numbers

Block Type	Typical Block Dimensions	Final Quantities
Primary (or Birthing) Block (as extracted from excavation)	Length: up to 6m Width: 750mm and 1000mm Depth: 1300 to 1400mm (determined by saw size)	3897 primary blocks
Processed Blocks (many primary blocks were cut lengthwise to increase yield)	Length: up to 4m Width: 750mm and 1000mm (not changed) Depth: 400mm to 1300mm	7564 processed blocks

2.2 Sandstone Quality Specification

A Sandstone Quality Specification was developed by the main contractor with input from various specialists, including the contractor's geotechnical advisor, the quarrying contractor, the stonemasons, and the client's advisors. The Specification presented a flow chart process that resulted in a final grading for the individual primary blocks, before final processing (saw-cutting and trimming) by the stonemasons. The grading classification adopted is a simple, two-code, grading based on final placement: N or S (for North or South zones); and Dry (for land placement above the Highest Astronomical Tide (HAT) level, or Wet (for submerged blocks below Lowest Astronomical Tide (LAT)), or Tidal (placed between LAT and HAT). A summary of the flow chart process is presented in Table 2 below.

Table 2: Flow chart process for sandstone block grading

Flow Chart Process	Verification Methods	Grading Assessment	Secondary Processes and Testing
Step 1	Random testing of primary block using Schmidt Hammer (correlated UCS strength) Visual inspection (spot checks) by geotechnical consultant	For UCS < 15 MPa: DRY grading For UCS ≥ 15 MPa: apply secondary processes prior to final grading	Check of correlated UCS values with laboratory UCS and Point Load Index tests on recovered core samples
Step 2	For blocks with UCS ≥ 15 MPa. Determine appropriate secondary process that will help improve durability.	For blocks containing defects that can be improved significantly by secondary process > WET or DRY grading (assessed depending on volume requirements) For blocks with no defects, assign TIDAL grading	These include trimming to remove: - weak seams - open bedding planes - jointing (split block at joint) - removal of shale inclusions
Step 3	-	-	Final cutting and trimming by Stonemasons

2.3 Approach to Durability Assessment

The assessment of durability, in terms of placement on the foreshore, as defined in the Specification relies primarily on the assessment of intact rock strength and whether or not an individual block can be improved by trimming and removal of significant defects.

Due to construction program constraints, assessment of durability by laboratory test methods did not provide an input to the grading process. Nevertheless, the Specification did include durability testing as a means of validating the grading process as well as previous durability testing reported in a previous geotechnical report. Table 3 below lists the tests specified for this purpose.

Table 3: Durability test methods adopted for validation purpose

Test Type	Test Method	Sample Procedure
Sodium Sulphate Soundness (salt-attack)	AS 1141.24: this is an aggregate test that involves submitting the 53mm minus crushed fraction to 5 cycles of wetting-drying in 35% anhydrous sodium sulphate solution to measure % loss	Approximate 2-3kg of rock sample required (this was trimmed from selected blocks)
Point Load Index	ASTM standard method on cylindrical cores obtained from selected primary blocks	50mm diameter cores, 50 to 60mm length. Tests were carried out on both soaked and dry samples.
UCS rock strength	AS 4133.4.2	On 50mm diameter cores.
Dry Bulk Density and Moisture Content	AS 4133.2.1.1	50mm diameter cores, 50 to 60mm length
Particle Density and Mean Water Absorption	AS 1141.6.1	2-3kg of rock sample (trimmed from selected blocks)

The Sodium Sulphate Soundness test method (AS 1141.24) was specified because the Australian Standard for armourstone (AS 2758.6-2008) recommends this particular test method for assessing the risk to saltwater attack for water-facing, armourstone applications. However, the Standard was not specified for the sandstone block revetment (its primary function is not protective, but aesthetic). As a guide, it does provide some useful recommendations for assessing durability:

- Based on an Exposure Risk Classification of Low / Moderate / High (where any salt water exposure is either Moderate or High), sedimentary rock (which includes sandstone) is considered unsuitable (as armourstone) for any risk category other than Low;
- In terms of Sodium Sulphate Soundness test, in a High Risk situation the % Loss should be ≤ 6% and for Moderate Risk situations it should be ≤ 9%; and
- In terms of durability, AS2758.6 recommends the Wet/Dry Strength Variation test (AS1141.24) as the best index test to assess durability. Based on this test, the following limits are suggested:

  - High Risk: Wet/Dry variation < 25% and the Wet Strength should be > 150 kN
  - Moderate Risk: Wet/Dry variation < 30% and Wet Strength should be > 100 kN

where the variation is defined as $(D_{dry} - D_{wet})/D_{dry}$, as a percentage, with D being a load in kN. The variation is the approximate reciprocal (allowing for differences in test methods) of the Wet/Dry strength ratio, defined as the ratio of Wet strength/Dry strength. Pells (2004) reported that the Wet/Dry strength ratio of sandstone samples obtained from a number of breakwaters around Sydney typically range between 25% and 50%. These values imply a Wet/Dry variation of 50% to 75%. These results generally support the AS2758.6 assertion that sandstone is unsuitable as armourstone in marine applications.

Although recommended as a durability test, the Wet/Dry variation test was not specified in the Sandstone Quality Specification (due to the time required to conduct the test). Nevertheless, a total of 5 tests were carried out during the early works stage to obtain indicative values for the sandstone. For general durability assessment, a project-specific method was adopted to obtain indicative Wet/Dry strength ratios based on Point Load Index testing of core samples tested dry and wet after soaking overnight.

3 SANDSTONE EXTRACTION PIT

3.1 Overall Dimensions of Main Excavation

The main part of the basement excavation (excluding access ramps) is approximately rectangular in plan with overall dimensions of 117m by 36m and designed to accommodate two basement car park levels as well as sub-excavations for water storage and pump rooms. The design base of the excavation at the lower basement floor is approximately 7.2m below original surface level. The original ground elevation across the site was +3.2 m AHD. Allowing for about 0.5m of fill above the existing bedrock surface, the anticipated rock volume from the main excavation was approximately 37,000 m^3.

3.2 Extraction Pit Ground Model

The findings from previous geotechnical investigation reports formed the basis for the preliminary ground model of the Cultural Space excavations. A total of 21 boreholes evenly spread out across the excavation footprint were used to develop the ground model of the extraction pit. The preliminary ground model sub-divided the Hawkesbury Sandstone formation, over the full depth of the excavation, into 3 main units (identified as Units 1A/B; Unit 2 and Unit 3), based on differences in fabric and composition.

An approximate 3D model was generated through a series of 2D cross-sections cut through the excavation. Inferred layer boundaries were shown for the 3 main Hawkesbury Sandstone rock units identified in previous studies. One such cross-section, aligned N-S near the western edge of the excavation, is shown in Figure 2 below.

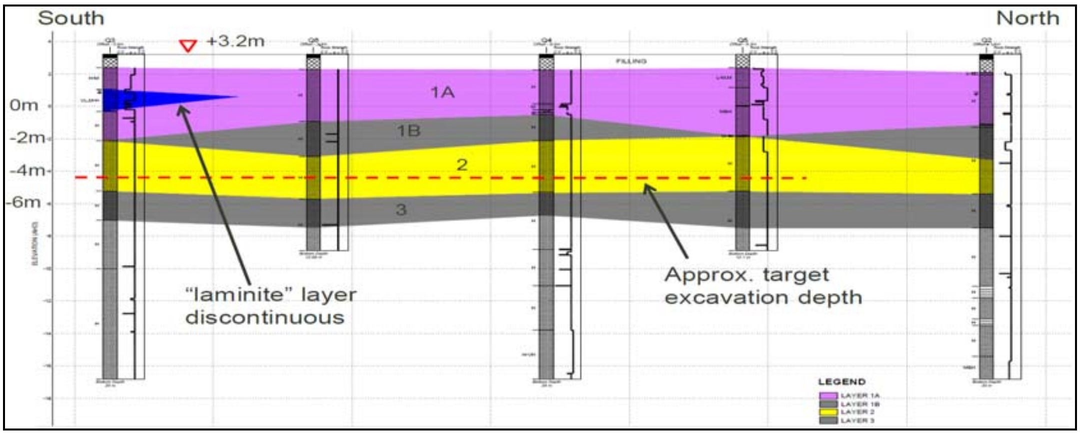


Figure 2. N-S ground model cross-section for excavation area

The characteristics of the 3 main Hawkesbury Sandstone units, as defined in previous geotechnical reports and from examination of available borehole rock core samples, are described in Table 4 below.

Table 4: Sub-division of Hawkesbury Sandstone formation adopted for project site

Unit	General Description	Petrographic features	Sandstone Class [a]
1	1A (upper 3-5m): yellow-brown to red-brown, medium to coarse grained, banded and cross-bedded, with shale interlayers up to 1m thick. Typically iron-stained. 1B (lower 1-2m): becoming grey to buff coloured, iron staining less evident (except along sub-vertical joints)	Quartz-rich sandstone with significant secondary quartz overgrowth. Clay/Illite/Mica content 3-11%; Siderite content < 1.5%	Class III to II
2	Yellow to off-white, generally massive, fine to medium grained. Colloquially known as "Yellow Block" (used in building industry as dimension stone)	Quartz-rich, argillaceous sandstone with moderate quartz overgrowth. Clay/Illite/Mica content 19-20%; Siderite content 5-6%	Class II to I
3	Grey to buff coloured, cross-bedded, medium grained (similar to sub-Unit 1B)	Quartz-rich, argillaceous sandstone with significant secondary quartz overgrowth. Clay/Illite/Mica content 16-17%; Siderite content 2-3%	Class II to I

[a] based on Bertuzzi and Pells (2002)

Based on the ground model and the design depth of the excavation, it was expected that the bulk of the excavation would be in Unit 1, with a few metres penetration into Unit 2 near the base.

4 EXCAVATION PROCESS

4.1 Pre-cut Trenches and Mapping

The geological ground model of the extraction pit was continuously checked and updated as the excavation progressed, achieved by regular inspection and mapping of both the vertical side cuts and the floor of the excavation. The information obtained by this mapping exercise was also used to advise the quarrying contractor on the optimum block width (and depth) that could be extracted from the current floor level. At each extraction level, a few narrow trench cuts were sawed across the floor of the excavation to permit visual inspection of the rock profile down the depth of the cut. In this way, it was possible to optimise the depth of cut to account for any weak seams or bedding joints that could naturally split during lifting of the blocks.

Each extraction layer was quarried in batches of 50 to 100 primary blocks in a sweep fashion across the floor of the excavation. On extraction, each block was assigned a unique identification number for tracking purposes. The system thus ensured complete traceability from extraction to final placement.

Six extraction levels were ultimately required to reach the base of the excavation. Extraction levels were identified by the designation EL-1 to EL-6. Subsequent mapping showed that extraction levels EL-1 to EL-4 were in Unit 1 sandstone, with Unit 2 sandstone intersected in extraction levels EL-5/6.

4.2 Spot Checking and Preliminary Grading

A preliminary placement grading was assigned by the quarry contractor during the extraction process when the blocks were individually assigned a tracking number.

Figure 3. View of extraction pit

The quarrymen's assessment was based on factors such as wear rate on saw blades, cutting production rate, as well as visual assessment of the general extraction layer rock fabric. The primary blocks were then moved from the extraction pit to a temporary stockpile yard. Whilst the blocks were in stockpile, spot checking of individual blocks was carried out by a geotechnical engineer. The spot checks were done in batches with the aim of visually checking around 10% of primary blocks obtained from each extraction level. A detailed geotechnical inspection report was produced for each batch, where notes were included for the attention of the stonemasons highlighting any weak zones, seams or jointing that should be trimmed off during the secondary processing. At this point in the process, core samples were obtained from individual blocks (for subsequent laboratory strength testing) in addition to random rock strength of checked blocks using a Schmidt Hammer tool. Based on the results of the spot checking, the geotechnical engineer determined a placement grading for each block inspected, and this grading was entered into the contractor's quality control register.

The main contractor ultimately decided the appropriate placement grading for all the blocks in any batch based on the spot check reports from the geotechnical engineer, and the quarrying contractor and stonemason's assessments. All blocks were individually marked with the assigned placement grading by the stonemasons following the secondary processing (at end of Step 2 in Table 2 above).

5 SANDSTONE BLOCK TESTING

5.1 Schmidt Hammer testing

An L-type Schmidt Hammer was used during spot checking of primary blocks for the purpose of obtaining a quick, on-site estimate of the sandstone intact strength. For this project, a site-specific correlation between UCS strength and the dimensionless Schmidt Rebound Hardness index ("R_h") was adopted based on the results of Schmidt Hammer testing of recovered rock cores obtained during spot checking of blocks from the first four extraction layers. Furthermore, a project-specific methodology was adopted for determination of the R_h index from a single test. A single Schmidt Hammer test consisted of 10 consecutive readings from the same spot on the rock core or block face. Analysis of the test data revealed that measurements became uniform after the first 2 to 4 readings. In view of this, for consistency, only the last 6 readings were used to obtain an average. In addition, for each test dataset, a mean (averaged) value as well as an upper-bound and lower-bound (averaged) value was derived using statistical analysis. Tests were done both axially and diametrically on the core samples.

The correlation was obtained by comparing the results of 12 no. UCS tests on individual cores against the statistically analysed results of Schmidt Hammer tests on the same corresponding cores. From this correlation the following general relationship was derived for the site-won sandstone:

UCS = [R_h – 24] in MPa (valid for R_h range 35 to 60)

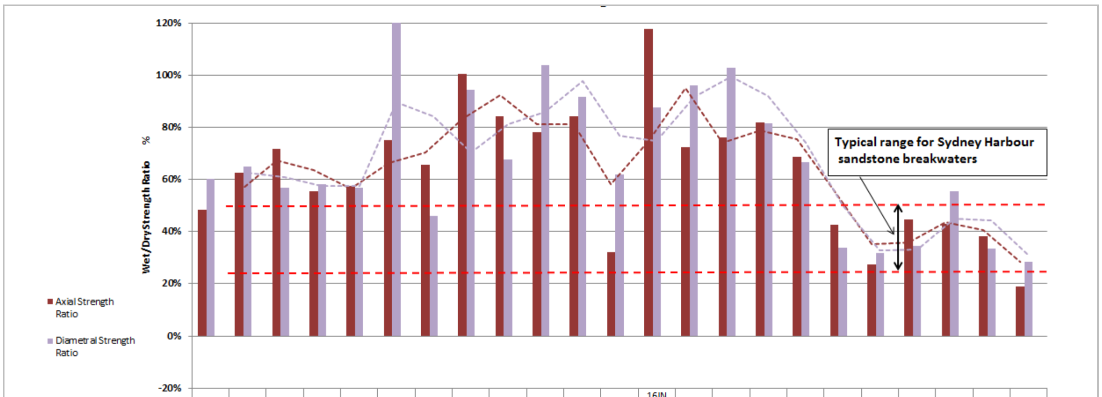
In total, 407 sets of Schmidt Hammer tests were carried out on sample blocks from all six extraction levels. The correlated UCS values obtained from these tests, using the correlation described above, ranged from 5 to 32 MPa with a mean value of 22 MPa. The mean UCS strength corresponds approximately to medium to high strength rock using the AS1726 rock strength classification. Of the total 407 results, only a small number (about 14%) produced values of 15 MPa or less. The above UCS strengths are generally typical of the range attributed to Class III sandstone (or better) from Pells (2002) classification, where weathering is generally limited to discontinuities in the rock mass. The Schmidt Hammer data was entered into a separate QC database that was used by the contractor to adjust the final grading of individual blocks (in terms of Dry, Wet or Tidal placement).

5.2 Point Load Index testing and laboratory UCS testing

As with the empirical, site-specific correlation obtained for the Schmidt Hammer R_h index, a similar correlation was derived between the laboratory UCS rock strength and the Point Load index (axial readings). A total of 11 sets of results were analysed and these revealed a wide scatter in the UCS/$Is_{(50)}$ ratio of between 8 and 22. The mean value is 13 and this was adopted for the site-won sandstone. This ratio is somewhat lower than the widely used indicative value of 20 suggested by Pells (2004) and others for Hawkesbury Sandstone, although these also vary significantly. The lower range derived from the sandstone at this site may be attributed to the weathering grade of the Unit 1 layer (Class III sandstone, generally, with much evidence of oxidation), from which most of the UCS test data was obtained.

The Point Load Index test was used primarily to assess the Wet/Dry strength ratios from testing rock core samples recovered during spot checking. The samples were tested generally dry (not oven-dried, but at natural moisture content typically < 2.7%), and also after immersion in water for a minimum period of 12 hours (saturated).

Figure 4 shows the distribution of Wet/Dry strength ratios obtained from testing of rock core samples from the six extraction levels. The trendlines show the ratio varies between 60% and 90% for the Unit 1 sandstone recovered from levels 1 to 4, reducing to between 30% and 50% in levels 5 and 6 (in Unit 2, or “Yellow Block” sandstone). This range is higher than that quoted by Pells (2004) for Sydney sandstones, but is better aligned with the estimated range of 60% to70% for cemented medium strength rocks suggested by Romana & Vásárhelyi (2007).



	187	2096	349	33	37	199	375	136	1921	151	1849	1579	16IN R10	1011	1716	1768	2859	2866	2948	51	3642	3651	3653
Axial Strength Ratio	48%	63%	72%	56%	58%	75%	66%	101%	84%	78%	84%	32%	118%	72%	76%	82%	69%	43%	27%	45%	43%	38%	19%
Diametral Strength Ratio	60%	65%	57%	58%	57%	123%	46%	94%	68%	104%	92%	62%	87%	96%	103%	81%	67%	34%	32%	35%	55%	33%	28%
Extraction Level	1	1	1	1	1	2	2	2	2	3	3	4	4	4	4	4	4	5	5	5	6	6	6

Sample

Figure 4. Wet/Dry strength ratios from Point Load Index tests on core samples.

5.3 Durability suite of tests

A limited number of durability suite of tests were carried out primarily for validating the strength and visual inspection approach to block grading adopted for quality control.

The rock strength test data has been discussed in the preceding sections. A summary of the remaining tests carried out is presented in Table 5 below.

Table 5: Summary of durability suite of tests (excluding rock strength testing)

Extraction Level	Particle Density (t/m^3)		Mean Water Absorption (%)	Sodium Sulphate Soundness Loss (%)	Bulk Density (t/m^3) [b]	Natural Moisture Content (%)	Wet/Dry Variation (%)
	Dry	**SSD [a]**					
1 to 6	2.15 to 2.37	2.27 to 2.47	4.0 to 5.9	Level 1: 14.8 Level 2: 48.1; 2.5 Level 3: 20.5 Level 4: 31.0; 3.0 Level 5: 8.3 Level 6: 28.8; 26.0; 45.3	1.04 to 1.25	1.7 to 2.7	51 to 80

[a] refers to surface-dry saturated density after 24hrs immersion; [b] uncompacted, obtained after crushing sample.

The density and moisture content data obtained is typical of relatively unweathered sandstones in the Sydney area. For armourstone applications, AS 2756.8 recommends that the dry particle density should be greater than 2.6 t/m^3 and the mean water absorption not exceed 1.5%. The results show that, as expected, sandstone is generally not a suitable armourstone rock type. The mean water absorption of sandstone reflects a relatively high porosity and thus susceptibility to salt penetration in marine environments. The Wet/Dry variation percentages are in the 50% to 80% range, which are high values, although again not unexpected for sandstone. As stated in section 2.3, the AS2756.8 armourstone specification recommends that this value should not exceed 35% even in a low risk situation.

The results of the sodium sulphate soundness tests (using the AS 1124 method) are shown graphically in Figure 5 below, together with data from previous reports (using the AS/NZS 5546 method). As can be seen, there is a wide scatter in the data, with most results exceeding 10% loss. Nominal upper-bound threshold values of 1% and 5% were assumed for low and high risk environments, respectively, based on the AS 2756.8 armourstone specification recommendations.

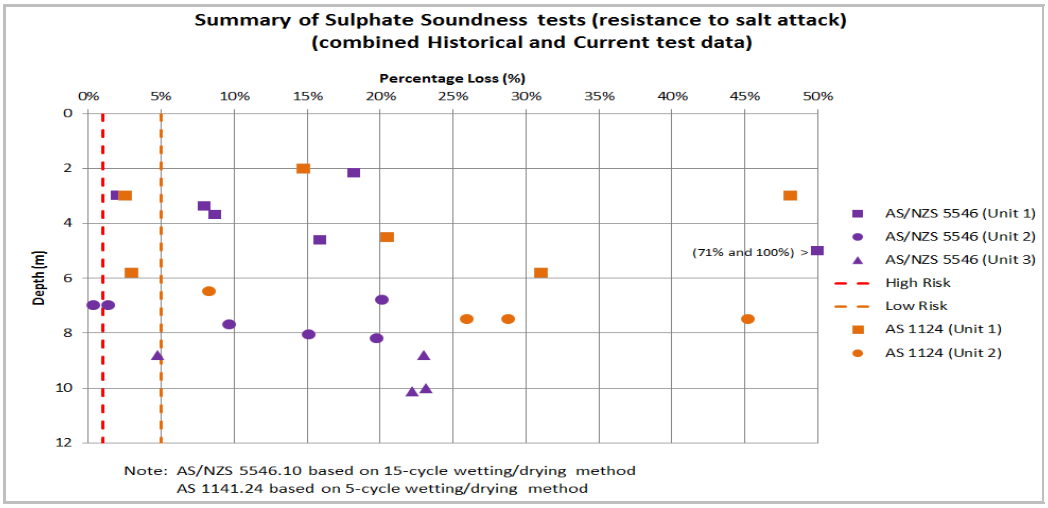


Figure 5. Sulphate Soundness tests per extraction level (historical and current data)

6 COMMENTS ON DURABILITY ASSESSMENT

The results from the durability suite of tests described above generally confirm that Hawkesbury sandstone is not a preferred rock type for marine, armourstone applications. However, the data itself is not an accurate predictor of the rate and form of deterioration that can be expected in a marine and/or salt-rich environment. There is ample practical evidence of the resilience of Sydney sandstone from existing seawalls around Sydney Harbour that are over a century old and still in reasonable good condition. Furthermore, Hawkesbury Sandstone and in particular the "Yellow Block" formation, has been used historically since the 19th century as a desirable building stone in many Sydney historic buildings.

In a recent publication, E. McSkimming (2011) presented an overview on durability of sandstone as a building stone, as well as the results of a study on two exterior samples of "Yellow Block" extracted from the Australian Museum in Sydney (founded in 1827). The study highlights the following observations:

- Degree of saturation and porosity (the latter being related to mean water absorption) are poor indicators of durability;
- Repeated wetting and drying with saline water, as would occur in the Tidal zone, has the most pronounced effect on erosion and deterioration;
- Rock density is a poor indicator of durability;
- The sodium sulphate soundness test, although a useful indicator of susceptibility to salt attack is not a conclusive indicator of durability, as other factors can have a contributing effect to deterioration;
- The UCS strength (dry) and the Wet/Dry strength ratio are considered to be the most useful and practical indicators of long-term durability.

In conclusion, the results of the durability suite of tests undertaken on a selection of samples of the site-won Hawkesbury Sandstone are comparable with similar, but limited data from previous studies and confirm that the sandstone is not particularly suited for marine, armourstone applications. However, the requirement for this project was for a sandstone foreshore that matches the existing façade of the Hawkesbury Sandstone rock cuttings and exposures in the area. A key premise of the design is that, although some deterioration of the sandstone block foreshore would be expected over the 100-year design life, this should not be to the extent that the functionality of the foreshore revetment is comprised.

Anticipating from the onset the known durability properties of sandstone, a Quality Control process was developed and implemented during the sandstone block extraction operations that aimed to quantitatively and qualitatively assess and screen every batch of blocks extracted and apply a grading in terms of final placement. As part of this, simple and practical geotechnical field and laboratory test methods were applied, supplemented by visual inspection of individual blocks to assess zones of weaknesses and/or defects. The process relied on UCS rock strength as the key geotechnical indicator and helped to ensure that the best quality blocks were selected for placement in the Tidal zone of the foreshore, this being the most aggressive zone.

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REFERENCES

AS 1141.22-2008. *Methods for sampling and testing aggregates – Method 22: Wet/dry strength variation.*

AS 1141.24-1997. *Methods for sampling and testing aggregates – Method 24: Aggregate soundness – Evaluation by exposure to sodium sulfate solution*.

AS 2758.6-2008. *Aggregates and rock for engineering purposes – Part 6: Guidelines for the specification of armourstone*.

AS/NZS 4456.10-2003. *Masonry units, segmental pavers and flags – Methods of test. Method 10: Determining resistance to salt attack.*

Bertuzzi, P. and Pells, P.J.N. (2002). "Geotechnical Parameters of Sydney Sandstone and Shale". Journal of the Australian Geomechanics Society, Vol. 37, No. 5, December 2002.

McSkimming, E. (2011). "Deterioration & Weathering Effects on the Engineering Properties of Sydney (Yellow Block) Sandstone when used as a Building Material". UNSW Canberra at ADFA Journal of Undergraduate Engineering Research, Vol. 4, No. 1 (2011).

Pells, P.J.N. (2004). "Substance and Mass Properties for the Design of Engineering Structures in the Hawkesbury Sandstone". Journal of the Australian Geomechanics Society, Vol. 39, No. 3, September 2004.

Romana, M. and Vásárhelyi, B. (2007). "A discussion on the decrease of unconfined compressive strength between saturated and dry rock samples. 11th Congress of the International Society of Rock Mechanics.