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The role of petrography in the selection of sandstone for repair

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About the Speaker

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Her academic research is in the fields of minerology and petrology. She specialises in industrial minerals and rocks, including gemstones, heavy mineral beach sands, talc, magnesite, asbestos and a variety of building and dimension stone including slate, granite and sandstone. She is a member of numerous professional geological societies and is Honorary Editor of *The Australian Geologist*. In 1994 she was made an Honorary Member of the Geological Society of Australia in recognition of her services to the geological profession.

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The role of petrography in the selection of sandstone for repair

Brenda J. Franklin

Many of the heritage buildings in the Sydney area are composed, either wholly or in part, of local sandstone. On the basis of broad composition, colour and colour change, dimension sandstone can be classified into six groups. However, most Sydney sandstone buildings are composed of either/or both of (a) 'yellow block' sandstone and (b) quartz-rich sandstone.

The well-known Sydney 'yellow block' sandstone is a true dimension stone, which is grey when quarried, but oxidises and darkens on exposure to the atmosphere to a warm yellow-brown colour. Quartz-rich sandstone is white, grey or pale yellow in colour when freshly quarried and does not darken or change colour significantly on exposure to the atmosphere.

Sandstone is a natural product with physical properties, including colour, texture and pattern, and strength parameters that can vary widely, even within the same quarry. Dimension sandstone has to meet certain requirements relating to the quality of the stone before it can be considered suitable for use as a replacement stone in restoration work. Test procedures to determine quality include an investigation of the petrography of the stone by means of microscopic examination.

Petrography identifies the minerals and the texture of a rock and can be specially tailored toward those features, which are important to dimension sandstone. A number of petrographic factors can be identified which affect the durability and performance of dimension sandstone.

Examples of the use of petrography in elucidating various problems relating to durability are given. Petrography can be used to scientifically establish whether an observed discontinuity is likely to lead to structural failure or not. It is also able to detail the style of weathering and decay of sandstone with depth. This aids in the decision-making processes of architects and engineers with respect to the amount of stone replacement required during stonework restoration.

The nature of ‘Sydney dimension sandstone’

Sydney’s heritage sandstone buildings, both public and privately owned, are composed of a number of different varieties of locally obtained sandstone. Depending upon the fancy of the particular architect at the time, sandstone in Sydney has been used for entire buildings from the foundations upward, including steps, stairways, columns, carved mouldings, etc. or simply for the footings of buildings with the rest of the building built in bricks or other material. Many churches and public buildings use sandstone for window sills and lintels to create a dramatic effect.

Sometimes when money has been short, only the front of the building is constructed in sandstone with the other walls of less expensive materials.

Additionally, most of the seawalls around Sydney Harbour and along the Parramatta River and the decorative landscaping features of the Sydney scene, including innumerable garden walls, paved and flagged areas and steps are also composed of the same stone. The term 'Sydney sandstone' is a colloquial one and refers to all or any of the above stones, which have been used as dimension stone.

On the basis of broad composition, colour and colour change, dimension sandstones can be classified into six groups (Table 1). All varieties are a quartz sandstone with a dominantly argillaceous or clay matrix (binder), but differ slightly in their mineralogy, quite widely in their mineral percentages and bedding features, and in their grainsize and porosity. Table 1 distinguishes the six groups together with examples of corresponding buildings and other structures.

TABLE 1: Classification of Sydney Dimension sandstones based on lithology, colour and colour change, with examples

GROUP	SANDSTONE TYPE	FRESH COLOUR	AGED COLOUR	EXAMPLES
1. **Grey Sandstone** (argillaceous)	(a) Gosford grey	Grey	stable grey	Wintergarden Plaza(?)
	(b) Wondabyne grey	grey(to cream)	stable grey	{Qantas Bldg; Science House; {Comm Bank Martin Place; City
	(c) Wondabyne Buff	grey(to cream)	grey to yellow-buff	{Mercantile Bldg; MLC Building; {DJs Castlereagh St; Gowings
	(d)'Mtn White' Springwood	grey to white	stable to pale yellow-buff	domestic bldg.; landscaping, lower Blue Mtns, west of Sydney
2. 'Yellow block' Sandstone (argillaceous) oxidising or 'self-colouring' sandstone	(a)CBD, Pyrmont, Maroubra, Bondi, Paddington, etc	grey-white	yellow-brown	many Sydney CBD buildings: e.g. Lands & Ed Depts; Art Gallery; Aust Museum; St Mary's Cathedral; State Library.
	(b) Debden	grey-cream	brown, orange, greyish, brown	Museum of Sydney; 'new' Sydney Eye Hospital
	(c) Piles Creek "Guinea Gold"	grey-cream	yellow, orange deep brown	Pyrmont Point Park
	(d) Bundanoon "Heritage"	light grey	light yellow to yellow-brown	Parliament House, Canberra; kerbing, Rocks; Strickland Park

3. White Sandstone (argillaceous)	Piles Creek White	grey-cream	slight cream to pale buff	Exterior panelling, Gov Macquarie Tower
4. Quartz-rich Sandstone (quartzose)	(a)Numerous built -over quarries in & around Sydney & Sydney Harbour	grey to white or very pale yellow	stable, to very pale yellow	Sydney Observatory; St Andrews Cathedral; Fort Denison; Powder Mag, Goat Is; east side Main Quad, Sydney Uni; etc.
	b) Kurrajong 'Bull Ridge' white	white	stable, may get a yellow-buff tinge	Bradley's Head landscaping; facade 155 Kent St Sydney; etc.
	(c) Appin SS, Wilton	grey to white or very pale yellow	stable, to very pale yellow	Campbelltown Courthouse; Nicholson steps at Sydney Uni.
	(d) Sandy Point, Quarry Heathcote	white, grey dark brown	stable	currently used as armourstone; dimension blocks recently cut
5.Colour-banded Sandstone (quartzose and/or ferruginous)	(a) Pymble, Hornsby,Maroubra	white, buff & brown or pink	stable	domestic/landscaping uses, in Sydney suburbs
	(b) Somersby	white to reddish brown	stable	many domestic/public building uses as cladding, landscaping
	(c) Mt White	off-white to brown & maroon	stable	domestic/landscaping uses including tiles for export market
	(d) Bundanoon banded	white to yellow or red brown	stable	Goulburn Courthouse & Gaol; domestic/landscaping uses, especially in southern Sydney
	(e) 'Yellow Rock' banded Springwood	white to yellow or red brown	stable	domestic, landscaping uses, especially in lower Blue Mtns; Long Reef Headland monument
6. Typical surface Hawkesbury SS (quartzose and/or ferruginous)	weathered, classified by colour & stone size	all colours:grey white, yellow, orange, deep brown & banded	stable	landscaping stone, for 'bush rock', innumerable walls, flagging & paving in Sydney area

In the CBD of Sydney, and immediate surrounds, and in numerous Sydney suburbs, many of the older sandstone buildings, including most heritage buildings and the Sydney Harbour sea walls are composed of either/or both of:

1. the well-known Sydney 'yellow block' sandstone, and
2. white, grey or light yellow quartz-rich sandstone, (Table 1 Groups 2. and 4.).

Sydney 'yellow block' sandstone (Table 1, Group 2).

Sydney sandstone, known colloquially as 'yellow block', is a true dimension sandstone and at its best, is a superb carving stone, which was much sought after by the masons in the last century. It is a fine- to medium-grained sandstone, which is massive in appearance, yielding large blocks of homogeneous stone. The stone has a moderate quartz content (60-68%) and is quite rich in soft clay (16-25%), which is why it carves so well. The stone is typically light grey when quarried, but contains small percentages (usually 2 to 7%) of the iron carbonate mineral siderite, which oxidises and weathers on exposure to the atmosphere, releasing iron-rich solutions which darken the stone and colour the clay binder at the surface a pleasant yellow-brown. The stone is known as a 'self-colouring' sandstone. The colour change usually takes a few weeks to a few months to occur.

'Yellow block' sandstone, which originally came from quarries in Pyrmont, Ultimo, the Sydney CBD, Paddington, Bondi and Maroubra has been used extensively in Sydney's great public buildings of the mid- to late nineteenth and early twentieth century, including the Lands Department and Education Department Buildings, Sydney University Great Hall and parts of the Main Quadrangle, the Chief Secretary's Building, the Australian Museum, the Art Gallery, the State Library, Sydney Central Railway Building, St Mary's Cathedral and many others. The quarries from which the stone came are now mostly built over. The last of these in the Bondi area, closed in 1986.

More recent and current sources for 'yellow block' sandstone are the Debden and Piles Creek (var. 'Guinea Gold') sandstones from Gosford Quarries Pty Ltd, at Somersby on the Central NSW coast, an excavation site in Kent Street in the Sydney CBD (now built over) and various other excavation and development sites in the Sydney CBD and along the Pyrmont Peninsula (e.g. the site of the 'Capitol' apartments on the corner of Pyrmont Bridge Road and Union Street, excavated in late 1996). Excavation sites containing possible reserves of 'yellow block' sandstone, which are currently under consideration for use as a dimension stone include St Patrick's Redevelopment Site, in the Rocks area and the 'Bauhaus' Development site, cnr Pyrmont Bridge Rd and Harris St, Pyrmont. All of the last three sites, however, have yielded or are likely to yield only relatively small amounts of usable dimension sandstone - usually less than 1,000 cu m^3.

Quartz-rich Sydney sandstone (Table 1, Group 4).

A siliceous or quartz-rich variety of Hawkesbury sandstone, which is white, grey or pale yellow in colour when freshly quarried. On exposure to the atmosphere the stone usually does not darken or change colour significantly, but remains close to its original quarried colour. This type of stone may be massive in appearance, but commonly contains a fine cross-bedding and/or colour banding. The stone is medium- to coarse-grained and contains more quartz (70-80%) and less clay (8-14%) than 'yellow block' sandstone. The stone may contain some quartz pebble either in single fragments or in layers, but very little or no siderite. It is more porous than the 'yellow block' varieties, often with holes or voids clearly visible to the naked eye.

Massive and lightly colour- and cross-banded quartz-rich sandstone was used extensively in the early days of the Sydney Colony, on buildings such as Fort Denison, the Queen's Magazine and Cooperage of Goat Island, the early part of the Sydney Observatory, St Andrew's Cathedral, the eastern side of Sydney University main quadrangle, Boyd Tower, near Eden (the stone was transported from Sydney by barge from the Pyrmont area), the old Bond Warehouses in the Rocks area, Farm Cove seawalls and many more. It was even used as paving stones and steps on Norfolk Island after travelling as ballast (from Ballast Point, Balmain) in ships returning to Norfolk after bringing calcareous stone from there to Sydney to make concrete.

It is likely that the quartz-rich sandstone cropped out extensively around the Sydney Harbour foreshores and on the islands within the Harbour, and of course at the Rocks, in the vicinity of the Sydney Observatory and on the hill where the Main Quadrangle of Sydney University now stands. It was used extensively prior to the 1850s, when the exploitation of 'yellow block' began. Much of the stone probably came directly from outcrop, as well as from specific quarry sites, with the stonemasons simply using the local, closest stone. Known quarries in quartz-rich sandstone occurred on Observatory Hill, Goat Island, the Domain and Bennelong Point.

Current quarry sources for the quartz-rich sandstone are the Appin sandstone quarry near Wilton, south of Sydney, the white and light brown 'Kurrajong' sandstone from the Bull Ridge Road Quarry near Kurrajong, some parts of the Sandy Point Quarry, near Heathcote and the Bauhaus development site mentioned above, where the stone has intermediate geological properties between 'yellow block' and quartz-rich sandstone.

Geology of Sydney sandstone

Geologically, the sandstone used for the buildings in Sydney comes from two main units called the Hawkesbury Sandstone and the Narrabeen Group sandstones which lie directly below the Hawkesbury. Hawkesbury Sandstone dominates the landscape within a 100km radius of Sydney. It is a flat lying sandstone of Middle Triassic age - about 230 million years old with an a real extent of about 20,000 square kilometres and a maximum thickness of about 250 metres. Most of Sydney's sandstone probably formed when the region was under water. The rocks were not formed in an ocean environment but as sandbars at the mouth of a massive river delta system such as todays Bramahputra Ganges Delta in India (Conaghan 1980) or the Amazon in South America.

Sydney sandstone is found in almost horizontal layers, which may measure from less than 1cm to several metres thick - average ~30 cm.

The layering usually consists of beds of coarse and fine sand and pebbly sands. The segments that divide one bed or layer from another appear on the face of the stone as parallel lines called bedding planes. They are weaker than the rest of the rock and are therefore more susceptible to weathering and erosion. Fossil traces e.g. ripple marks, tracks of birds, remnants of leaves and twigs, etc., are often found in the bedding plane.

Sometimes the layers run diagonally or obliquely across the main bed, and this is called 'current' or 'cross' bedding. Cross bedding is a characteristic of Sydney sandstone, where the main layers are horizontal, but within it are layers of thin strata lying at an angle to the horizontal. Cross bedding is caused when a shallow current carrying sand particles enters deeper water and the velocity of the current slows and the grains drop out of the water and slide down the slope of the outermost advancing edge of sediment. As each layer accumulates the outward extension of diagonal strata grows. Cross bedding is also caused by deposition of sand grains at a steep angle of repose, such as on the side of a sand dune.

Other structures in Sydney sandstone result from joints or cracks, faults and even volcanic activity. Joints allow surface water to penetrate deep underground. The surface of joint faces and the adjacent area of sandstone are often coated by iron oxides to a dark red-brown colour.

The value of petrography in determining the physical properties of dimension sandstone

Sandstone is a natural product and its physical properties including colour, texture, pattern and strength parameters can vary widely, even within the same quarry. Before a sandstone can be considered suitable for use in restoration work for repair of heritage buildings, it has to meet certain requirements relating to the quality of the stone. These requirements are in terms not only of aesthetic properties such as colour and surface features, but also, and very importantly, in relation to strength, dimensional stability and durability.

Thus, specifications, detailing minimum requirements relating to stone supply are employed and the sandstone is tested by various procedures that are appropriate for the stone in a specific application. The test procedures consist dominantly of two types:

1. Laboratory engineering tests carried out to a set of standards, which determine the various physical parameters of the stone. Such tests include water absorption, bulk density, unconfined compressive strength, modulus of rupture, flexural strength, modulus of elasticity, impact resistance, resistance to abrasion, coefficient of thermal expansion, etc.
2. Determination of the petrography of the stone by means of microscopic examination, which may be augmented where required by X-ray diffraction analysis and scanning electron microscopy techniques, etc.

Petrography is simply the geological description and classification of a rock, usually by means of microscopic examination.

A straightforward, geological description of a stone, together with its proper geological name, is internationally recognisable. In the case of petrographic descriptions of sandstones a fuller appreciation of the geological history, which in turn affects both the physical properties and the durability of the stone is obtained (Palmer 1995).

A petrographic analysis is made in two parts (Table 2). Firstly, the mesoscale or visual assessment of the specimen in hand specimen using the naked eye, a hand lens and/or low power binocular microscope, followed by microscopic analysis using a standard petrological microscope and a thin section, which is a carefully ground slice of the rock (0.03 mm thick) cemented onto a glass slide. At this thickness, most minerals in the rock are transparent to light. With sandstones, it is particularly important to study the character of the void spaces in the rock. This is done before grinding, by impregnating the rock slice in a green vegetable-dyed resin, which fills all the pore space, even down to less than 0.001 mm and makes it instantly recognisable down the microscope or in colour photos.

The typical procedure for the petrographic analysis of a dimension sandstone is as follows:

TABLE 2: OUTLINE OF PROCEDURE FOR PETROGRAPHIC ANALYSIS OF DIMENSION SANDSTONE

Mesoscale or visual assessment in hand specimen
(using naked eye, hand lens and/or low power stereomicroscope)
The pertinent features include:

1. Determination of the mineralogy of the stone, including:
    - identification of any minerals and/or rock fragments large enough to be seen (e.g. quartz, lithic fragments) or with distinctive properties at this scale (e.g. mica, tourmaline)
    - identification of the nature and amount of any binder. (Dilute hydrochloric acid (1M to 5M concentrations and possibly warmed) may be used here to determine the presence or absence of carbonate minerals).
    - Examination for the presence of any post-depositional quartz overgrowth (usually seen in sunlight - development of bright vitreous lustre on quartz crystal faces).

2. Determination of the texture of the stone, including:
    - layering or bedding features, including cross-bedding,
    - colour variation as related to mineralogy,
    - grainsize, grainsize range and rounding,
    - macroporosity - size and extent of any visible voids.

3. Determination of the presence and extent of:
    - pebbles and pebble bands,
    - shale inclusions and lenses,
    - carbonaceous matter and/or graphite or ‘tea leaf’,
    - kidney (ironstone concretions), carbonate concretions, sand balls, etc.

4. Recording of any visible signs of weathering and deterioration, including:
    - surface roughness to the hand,
    - ‘leaching’ or whitening of the stone,
    - excessive iron colouration (yellow-brown to orange) due to iron oxide/hydroxide deposition,
    - friability (pitting and sanding) of the surface (grains can be rubbed off by hand),

- exfoliation (mechanical spalling of the rock close to, or parallel to the surface),
- structural failure – fracturing, cracking of stone,
- any signs of increase in porosity due to erosion and removal of material (presence of visible holes).

Microscale
(features determinable only with a petrographic microscope)

1. Identification of all of the framework minerals and rock fragments present in the sandstone and their characteristics.
2. Determination of the mineralogy of the binder, including both matrix (such as clay minerals) and secondary cement (such as quartz, iron oxides/hydroxides and carbonate).
3. Identification of any detrimental minerals (e.g. expanding clays, sulphides, etc).
4. Analysis of the texture of the rock – how the framework minerals and binder are related, including grainsize, rounding, sphericity, etc.
5. Analysis of the porosity and permeability - the extent and size and interconnection of void spaces.
6. Identification of the extent of weathering and decay (alteration) of the individual minerals and their weathering products.
7. Determination of any textural breakdown due to removal of material (erosion) and to mechanical disintegration (the occurrence and extent of any microfracturing/faulting both within and between individual minerals).

Advantages

1. The amount of material required for analysis is only small - about a fist-sized piece of stone.
2. Low cost - approx. $150 per sample (and approx. $250 for an X-ray diffraction analysis if required).
3. Speed of results. An actual petrographic analysis takes approximately 1 to 1½ hours. The lead time is the construction of the thin section necessary for microscopic examination, which may take up to 3 days.
4. Once typical features of a stone are established for a particular quarry, there is a great advantage to the supplier who can be quickly informed of the likelihood of rejection before sending stone to be processed (or delivering stone to site).

Disadvantages

1. The small amount of material not used for testing is not necessarily representative of the quarry, quarry block and/or processed stone block as a whole.
   (NOTE: This statement *could and does, equally apply* to the selection of a block of sandstone for laboratory engineering tests.)

   Sampling is the most critical factor in the reliability or not of a petrographic analysis for the suitability of a sandstone as a dimension stone. Because the properties of a sandstone are so variable every quarry site has to be tested independently. Sampling of representative material is thus vital and can affect results markedly.

2. The experience, personal judgement and competency of the petrographer. Petrography is largely a 'learned' science where experience plays a significant part. Sandstones are quite difficult rocks to interpret.

A routine petrographic examination of a stone may emphasise features, which are not of any particular significance in a dimension stone. As a corollary, there are special properties required in a dimension sandstone, which may not be particularly emphasised in a routine petrographic identification (e.g. presence of any deleterious minerals, amount and nature of secondary quartz overgrowths, the visible permeability as against the porosity). *A useful petrographic analysis MUST be specially tailored toward those features, which are important to dimension sandstone i.e. stone which is to be used in the built environment.*

3. Petrographic tests of dimension sandstone are far more instructive and rigorous when carried out on a comparative basis rather than 'stand alone'. A single petrographic analysis of a sample from an unknown location with no basis for comparison is usually inadequate, unless there is overwhelming mineralogical and textural evidence that the stone is clearly unsatisfactory or totally superior. Most sandstones fall somewhere between these two extremes.

Petrographic factors affecting the durability of Sydney sandstone

Petrographic assessment of sandstone for strength and durability, is governed by a number of geological factors, including both mineralogical and fabric elements. Some of the most important factors are:

1. Amount of secondary silica deposition (i.e. direct quartz-quartz contacts).
2. Amount and nature of the clay matrix (or binder) in the stone,
3. Porosity (i.e. volume percent of voids),
4. Freshness (i.e. lack of alteration) of constituent minerals,
5. The amount and degree of alteration of siderite.
6. The presence of iron oxides/hydroxides.
7. The presence of discontinuities and/or zones of structural weakness in the stone.

1. Amount of secondary silica deposition

Quartz or silica (SiO_2) is dominantly present as grains in the original sand. Quartz content of typical Sydney 'yellow block' sandstones spans a fairly narrow range from 61-68%. In the quartz-rich sandstones the quartz percentages range from 70-80%.

During compaction and conversion of the sand into a solid rock - sandstone - some of the original quartz dissolves during this consolidation process by means of a mechanism known as pressure solution, and immediately re-deposits in the voids or holes adjacent to other quartz grains in the form of overgrowths on the original detrital grains, cementing the original quartz grains together, often decreasing the porosity and forming a rigid framework and increasing the strength of the rock.

Additional silica can also be introduced into the sandstone from outside sources during its consolidation, enlarging the original quartz grains and decreasing the porosity.

Where overgrowths are well-developed the overall shape of the grains changes from rounded to subangular with the 'secondary' quartz forming quartz crystal faces with a characteristic glassy lustre which is obvious in the stone in direct sunlight.

The greater the amount of secondary quartz the greater the strength and likely durability of the sandstone.

On the basis of percentage of secondary quartz content, the highest amounts of secondary quartz in 'yellow block' sandstones are found in stones from Pyrmont, Ultimo, Kent Street, Maroubra and Bondi. All the quartz-rich varieties have a high amount of secondary silica (Franklin 2000 *in press*).

2. The nature, percentage and distribution of the clay minerals in the rock.

Clay/illite minerals occur singly or together in finely-crystalline mixtures. They occur in both rounded and elliptical aggregates (or pellets) and as a binder or matrix. The clay minerals/illite mixtures vary from light grey to pale yellow in colour, the usual amount varying broadly between 5% and 30%. Occasionally, clay-rich varieties of Sydney sandstone occur. These would not be considered as suitable for use as dimension stone.

The nature of the clay minerals in Sydney sandstone is variable. As well as stable minerals of the kaolinite and sericite/illite group, small amounts of less stable swelling clays (illite/smectite) have been identified. Identification of individual clay species requires X-ray diffraction analysis methods. It has generally been agreed that the presence of swelling clays in Sydney sandstone are not likely to be derogatory to the stone’s performance. e.g. Previous X-ray diffraction analyses (Coffey Partners Report, July 1991) of rock core material from the Pyrmont site.

Clay minerals, however, are soft and easily removed by mechanical surface processes such as water and wind erosion, and by the pressures of continual salt crystallisation or by abrasive methods of surface cleaning. High percentages of clay in a sandstone (say >25%) are indicative of a soft stone of probable less durability (Winkler 1994).

3. Porosity

In petrographic analysis by thin section, porosity is estimated as a volume percent of the voids (or spaces) in the rock. As mentioned earlier, to facilitate this calculation, the voids on the surface of a cut slice of the rock are filled with a bright green dyed epoxy cement before the rock slice is mounted on a glass slide in preparation for grinding to thin section thickness. Volume percent can be determined quite accurately, using a point counting method and individually counting the bright green areas using a grid pattern. The percentage of voids (pores), their size and distribution - whether or not they are interconnected (permeability) helps to determine the strength and durability and also permits estimates of moisture content and the movement of moisture and salts through the stone.

4. The freshness of the rock

Fresh or only slightly weathered sandstone is likely to be more durable than stone where the minerals have been partly broken down and degraded by the various weathering processes. Decomposition and disaggregation of the rock fabric increases with increased weathering. While quartz, and clay/illite are very stable in the surface environment, other constituents of typical Sydney sandstone, notably siderite (Fe, Ca carbonate), and to a lesser extent the more coarsely crystalline white mica (muscovite), are likely to show signs of staining and/or alteration - around edges, along cleavage planes and possibly throughout the whole body of the mineral if weathering has occurred. Visible signs of weathering and deterioration are mentioned above in the mesoscale assessment, during petrographic analysis of the stone (Table 2).

5. Amount of siderite

The percentage, distribution and freshness of the minor carbonate mineral (siderite) is an important factor in the durability of Sydney sandstone. Siderite is a carbonate mineral, formed during the consoolidation of the sand into sandstone (diagenesis). It is the partial breakdown of siderite, following exposure to the atmosphere, on the surface of a quarried stone, which is most likely to be responsible for the surface 'yellowing' of 'yellow block' sandstone.

When fresh or only slightly altered, siderite forms an additional reasonably strong binder material. However, sandstones with larger than usual amounts of siderite (say > ~10%), although initially strong, have often performed badly on site in Sydney's warm, coastal climate (cf. some of the Bondi stone on St Mary's Cathedral, put in as a replacement stone in the 1920s). The carbonate mineral eventually breaks down in the acidic wet Sydney climate and becomes very weak. The effect of this breakdown on stones with smaller amounts of siderite is correspondingly less.

6. Secondary iron oxides/hydroxides

Iron-bearing minerals in sandstone are mainly limonite ('rust'), goethite and hematite, which form both during diagenesis and during surface weathering of the stone. They occur replacing siderite and any other of the constituent minerals, which may contain small amounts of iron, such as the clay/illite minerals. Iron in its less oxidised state (ferrous iron, Fe^{2+}) forms a number of slightly soluble compounds under surface acidic oxidising conditions, which may be removed from the stone in solution. Once completely oxidised to ferric (Fe^{3+}) compounds, iron compounds are far less soluble under normal surface conditions. An example of this occurs in 'case-hardened' surface stone where the clay matrix is partly or wholly replaced by relatively insoluble dominantly ferric iron oxides/hydroxides and the porosity of the stone is decreased.

7. The presence of planes and zones of structural weakness in the stone

Any form of discontinuity in stone may indicate a potential zone of structural weakness. The presence of bedding plane structures including compositional and grainsize changes, depositional discontinuities, parting planes, cross-lamination, shale lenses, sand balls, carbonate concretions, excessive carbonaceous material ('tea leaf') and graphite, fractures, cracking, joints, etc., etc., will almost certainly affect the durability of the stone adversely.

Conclusions

Unfortunately when it comes to weathering and decay, sandstone is not physically robust like granite or basalt and Sydney has had very high pollution for most of this century, first from the steam trains, then from coal-burning power stations and now with an excess of fumes from cars - and all in a warm and windy, damp, salty climate. There are chlorides, nitrates and sulphur compounds in abundance in the atmosphere, all of which form acid rain. 'Yellow block' sandstone in particular does not stand up well in this type of environment and many of the fine buildings of the last and early this century are in need of repair and replacement of parts of the stonework.

The most commonly called-for replacement sandstones in heritage building restoration are projected and decorated masonry elements, having many exposed bedding planes and crevices, such as cornices, coping stones and carved and moulded features. These units are highly vulnerable to the processes of decay and must be carefully selected to be stone of high durability and aesthetic quality.

'Yellow block' sandstone varies quite a deal in its durability, ranging from moderate to very good. Dimension sandstones must pass minimum specification requirements in laboratory engineering tests such as those demanded by the NSW Department of Public Works and Services before their use as a replacement sandstone for repair on heritage buildings can occur. The petrographic assessment of such stones will usually conform with the engineering tests - e.g. a 'yellow block' sandstone of high durability, which passes all of the engineering test requirements will almost certainly have a high percentage of secondary quartz, a low porosity, be unweathered, and have an absence of fractures, etc.

If a sandstone passes the specified requirements in the engineering tests except for say one or two tests, petrographic analysis can often provide the explanation - e.g. a stone passing all engineering tests except the wet modulus of rupture test may have too high a clay content for sufficient strength in a tensional environment.

Petrographic analysis can also be used to scientifically establish whether or not the presence of a particular visible discontinuity is likely to lead to structural failure of the stone or is just an aesthetic problem.

The fracture and failure of 'yellow block' sandstone containing the defect colloquially known as 'black line' has long been observed by stonemasons (Plate 1). The use of stone containing 'black line' has been excluded from carved and moulded work because of the high incidence of splitting and the increased danger of public injury and property damage. However, because its cause had not been scientifically established, the rejection of stone containing this defect on durability rather than aesthetic grounds was often challenged.

A petrographic analysis clearly identifies the problem to be in the mineralogy and texture (Franklin 2000, in press). In stone within and adjacent to a 'black line' there is (a) a four-fold increase in siderite, (b) a decrease in quartz and clay content and (c) a three-fold increase in porosity - all of which are petrographic factors which adversely affect durability. The petrographic analysis thus validates the rejection of stone containing this defect. Stone displaying this mineralogical distribution anomaly should not be selected as a replacement stone for overhanging and/or freestanding elements.

Petrographic analysis has also established why quartz-rich sandstone, despite its initial higher porosity, has proved to be a more durable stone in use than most 'yellow block'. This is because it depends for its strength on a significant amount of secondary quartz cement rather than on a low porosity and a higher percentage of softer clays (Franklin 2000, in press). Quartz-rich sandstone usually performs well in engineering laboratory tests, particularly the test for modulus of rupture or shear strength.

Finally, petrographic analysis can be extremely useful in diagnosing the pattern of weathering and alteration of dimension sandstone with depth, the degree of alteration and/or removal of the constituent minerals and the distribution of porosity and permeability in the rock. This aids in the decision-making processes of architects and engineers with respect to the analysis of the amount of replacement stone, which might be needed at a particular location during stonework restoration.

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