

## Characterisation of Irish sandstones used for building.

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**ABSTRACT:** This study examines several sandstones used in monumental and vernacular structures. They were sourced at Manorhamilton, Co. Leitrim; Clara, Co. Offaly; Drumbane, Co. Tipperary and Killaloe, Co. Clare. The Manorhamilton rock is used by the Office of Public Works for restoration while the Clara, Killaloe and Drumbane stones were used to build some of Ireland's most important monuments including Cormac's Chapel on the Rock of Cashel, St. Brendan's Cathedral, Clonfert, and Clonmacnoise Monastery. It is necessary to establish the properties of these sandstones to understand their current condition and facilitate decision making to conserve them. This paper determines composition, mass structure (density and porosity), moisture behaviour (capillarity and evaporation) and mechanical properties including compressive strength, modulus of elasticity and surface hardness. These properties largely determine compatibility between the sandstones and consolidant treatments as well as mortar repairs. All sandstones are siliceous, dense, strong, stiff materials of low porosity and permeability, brittle behaviour and typical shear failure. Their property values compare well with those of granite and other strong, durable igneous rocks. Therefore, in sound condition, they are compatible with mortars of medium to high hydraulicity. The Drumbane (siliceous variety), Manorhamilton and Killaloe sandstones are the strongest and stiffest; their strength and stiffness are well over those of Portland cement concrete and engineering grade brick. The Clara Hill is the weakest and less stiff sandstone however, its strength and stiffness are well over those of conventional building units, closer to engineering grade materials. In the most ferruginous sandstones (Drumbane and Clara Hill), there is an inverse relationship between compressive strength/density and iron cement (haematite): as the iron lowers, the rocks become denser and stronger as well as less porous and permeable.

**KEY WORDS:** Irish Sandstone; Density; Porosity; Capillary suction; Compressive strength; Elastic modulus; Surface hardness.

### 1 INTRODUCTION

This study is part of wider research carried out in the Department of Civil Engineering, Trinity College Dublin. The aim of this research was to preserve monumental Irish sandstone. Two conservation areas were considered: stone consolidation and the repointing of masonry with compatible mortars. Rocks lose material over time as a result of weathering. Consolidants are chemical substances aimed at replacing the cohesive strength between particles where cementitious materials have been lost. A variety of consolidants have been used on monumental stone. For this research, Tetraethoxysilane (TEOS) consolidants were chosen because they are silica based materials chemically compatible with most Irish sandstones; they have a significant history of use and are continuously available [1].

The mass structure, moisture behaviour and mechanical properties of the sandstones were investigated in order to ensure compatibility between the sandstone and conservation repairs including consolidants and mortars.

Penetration is essential for a consolidant to work and also to avoid damage to the substrate. Penetration relates to permeability which is determined by the mass structure and pore system characteristics therefore, the density, porosity, capillary suction and evaporation of the sandstones were investigated. Permeability and strength are critical properties in the context of consolidation: the treatment must not undermine the ability of the stone to follow the prevalent moisture regime and; in addition, the consolidant treatment

must not increase the likelihood of differential stresses developing between the outer exposed treated surfaces and underlying substrates.

In relation to mortar repairs, most historic and traditional masonries are built with lime mortars which weather over time and often need to be repaired. The new mortar needs to be compatible with the building units. Compatibility refers to chemical composition but also to physical properties such as strength and permeability. A mortar stronger and more impermeable than its substrate can damage the masonry as it drives moisture into the building units enhancing all weathering processes related to the presence and movement of moisture such as expansion by evaporation, freeze-thaw, mineral dissolution, biological colonization and salt crystallization. Therefore, the sandstone properties related to moisture transfer including porosity, capillary suction and evaporation, were characterised in order to ensure compatibility with mortar repairs. In addition, a mortar too strong and stiff does not accommodate movement transferring stresses to the masonry units which may eventually fracture. Therefore, the strength and stiffness of the sandstones were measured in order to ensure mortar compatibility.

### 2 MATERIALS AND METHODS

#### 2.1 Materials

The sandstones were sourced at Manorhamilton, Co. Leitrim; Killaloe, Co. Clare, Drumbane, Co. Tipperary and Clara, Co. Offaly. The Manorhamilton sandstone comes from the Mullaghmore Sandstone Formation in Co. Leitrim [2] and the

Killaloe sandstone from quarries near Killaloe town, on the River Shannon, in the mid-west of Ireland [3]. The Drumbane sandstone was sourced from a quarry north of Cashel, Co. Tipperary in the Cappagh White Old Red Sandstone Formation [4]; and the Clara sandstone from a quarry in Clara Hill, Co. Offaly. The Manorhamilton sandstone is currently used for restoration works while the Killaloe and Drumbane sandstones were used to build some of Ireland's most important national monuments. Drumbane sandstone can be seen in Cormac's Chapel on the Rock of Cashel. Killaloe sandstone can be seen in the doorway of St. Brendan's Cathedral, Clonfert and in the several structures at Clonmacnoise, which has been nominated for acceptance as a UNESCO World Heritage Site. The Clara sandstone was also used to build Clonmacnoise. The sandstones were tested according to EN standards and RILEM recommendations.

## 2.2 Petrographic Analysis, Density, Porosity, Evaporation and Capillary Absorption

Petrographic examination was carried out according to EN 12407 [5]. The mass structure properties were characterised by measuring the apparent density and open porosity in accordance with EN1936 [6]. Evaporation curves and water absorption by capillarity were measured in accordance with RILEM Recommendations [7].

The samples were dried in an oven at 105°C for 24 hours and the dry mass,  $m_d$ , calculated. They were then placed in a tray containing approximately 2mm depth of water and the capillary absorption measured by taking readings of time and mass,  $t_i$  &  $M_i$ .

The specimens were later immersed in water under vacuum pressure for 24hrs. The hydrostatic and surface saturated masses were measured,  $m_h$  and  $m_s$ . Finally, the samples were wrapped on 5 sides with cling film and left to dry, taking mass readings to measure evaporation with time,  $t_e$  and  $M_e$ . Readings were typically taken at 15mins, 30mins, 1hr, 3hrs, 8hrs, 24hrs and 48hrs.

$$\text{Apparent density (kg/m}^3\text{),} \\ \rho_b = m_d / (m_s - m_h) * \rho_w \quad (1)$$

$$\text{Open porosity (\%),} \\ p_o = (m_s - m_d) / (m_s - m_h) * 100 \quad (2)$$

$$\text{Evaporation rate (g/m}^2\text{/hr),} \\ q = m / t; m = M_w / \text{area}; M_w = M_o - M_i \quad (3)$$

$$\text{Capillary absorption rate (g/m}^2\text{/s}^{1/2}\text{)} \\ A = m / \sqrt{t}; m = M_w / \text{area}; M_w = M_o - M_i \quad (4)$$

## 2.3 Compressive Strength and Modulus of Elasticity

The compressive strength (maximum stress at failure -  $N/mm^2$ ), was determined according to EN 1926 [8]. Data for stress, strain and displacement were also obtained, allowing calculation of the modulus of elasticity ( $E = \text{Stress/Strain} - \text{equation 5} - kN/mm^2$ ). Strain gauges were attached to the faces of the specimens using an epoxy resin. The load vs strain was monitored using a System 5000 workstation connected to the strain gauges and a 100kN load cell.

$$E = \sigma / \epsilon \quad (5)$$

## 2.4 Surface Hardness

It was measured with a Schmidt hammer rebound which uses a spring mechanism to determine the strength of the surface. The samples were placed flat on a covered concrete floor, making sure that the bottom surface was smooth and resting uniformly on the floor. The piston was gradually pressed down onto the surface and the rebound of the hammer noted. This value is translated into compressive strength (uniaxial, unconfined) when used in conjunction with calibration charts.

## 3 RESULTS AND DISCUSSION

### 3.1 Petrographic Analysis

The Drumbane sandstone is a quartzitic sandstone of varying composition (Figure 1). Grey (siliceous) and rust (ferruginous) varieties were sampled from the quarries. The grey stone is well sorted with fine quartz and infrequent mica. It contains fine pores, some refilled by secondary iron, and fissures of clay or iron liable to open. Increasing iron turns the rock into a rust colour. The rust stone is also fine-grained but less dense. It contains significant clay mineral matrix and iron oxide cement (mainly haematite); and has a more open, fine-medium, pore structure. Haematite can also accumulate in layers (Figure 2).



Figure 1. Drumbane sandstone: abundant clay matrix and significant iron cement and pores. X2 polarized light



Figure 2. Drumbane sandstone: low porosity with clay mineral matrix and layered iron cement. X2 polarized light.

The Manorhamilton sandstone is a fine to medium grained, quartzitic sandstone with occasional mica and feldspar, clay mineral matrix and iron cement (Figures 3 and 4). Colour



varies from grey to brown and sand (finer pores), depending on the iron content. Variations can be seen along strata. The quartz grains are coarser where the iron and feldspar contents are greater. Pores have a wide size distribution (medium to very fine).



Figure 3. Manorhamilton sandstone with abundant quartz, little cement matrix and substantial pores. 2X polarized light

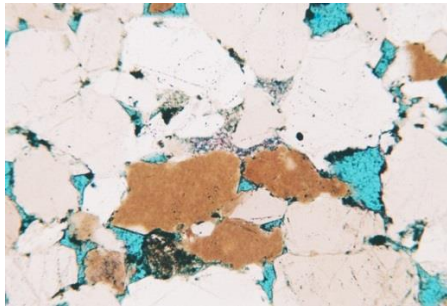


Figure 4. Manorhamilton sandstone detail of clay mineral matrix, quartz and pores. 10X polarized light

The Killaloe sandstone is a mature quartzitic rock with varying ferruginous content and large differences in colour [2]. It periodically contains mica, feldspar, clay mineral matrix and iron, silica and carbonate (dolomite) cements (Figures 5 and 6). The majority of the stone is dense and compact with low pore volume. Darker varieties are more weakly cemented and contain medium-coarse pores. The grey/green varieties include glauconite (Figure 6) and biotite.

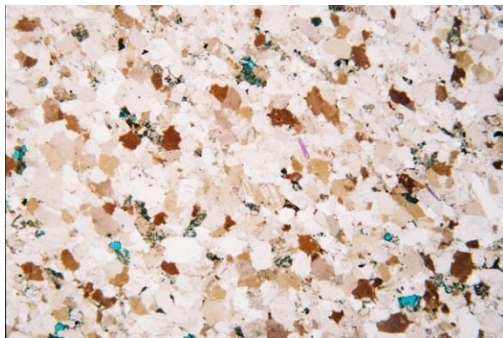


Figure 5. Killaloe sandstone including abundant quartz and scarce feldspar and mica. Low porosity. X2 polarized light.

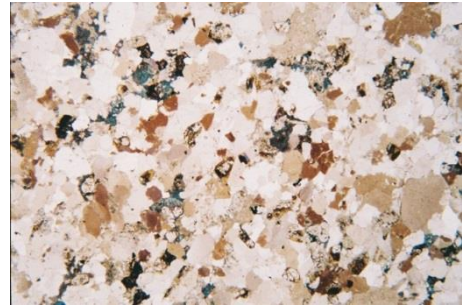


Figure 6. Killaloe sandstone: occasional carbonate cement (dolomite) and significant glauconite. X2 polarized light.

Table 1. Mineral composition and petrography.

	Drumbane	Manorhamilton	Killaloe	Clara Hill
Colour	grey, rust, brown	grey, white, brown, sand	buff, brown, grey, green	grey, white, yellow
Mineral composition	quartz 60 clay 15-30 mica <2 iron 6-15	quartz 70+ clay 5 mica <2 iron <6	quartz 85 clay, silica cem 5 mica, dol <2 iron 5-10 feldspar 5	quartz 60-80 clay 10-15 mica <2 iron 7-15 feldspar <2
(%by volume)				
Pores	Fine, occ. medium	Fine to medium, wide distribution	Fine to medium, Dark coarser.	Fine, coarser in yellow variety
fracture	occasional inter granular 0.1-1mm	occasional large inter granular 0.1-0.5mm wide.	occasional curved fractures with deposits	occasional open inter granular by >30mm

The Clara Hill sandstone is also quartzitic. It includes substantial clay mineral matrix and iron cement and a considerable pore volume with a wide size distribution (Figure 7). It periodically contains feldspar and mica. The yellow variety has more abundant clay and more abundant, coarser pores (Figure 8).



Figure 7. Clara Hill sandstone with abundant clay matrix and iron cement. X2 polarized light.

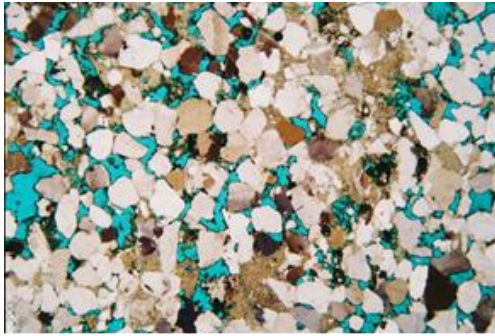


Figure 8. Clara Hill sandstone with significant clay matrix, iron cement and pores. X2 polarized light.

### 3.2 Density and Porosity

Most sandstones are dense materials of low porosity. The results agree with the petrography evidencing that the sandstones are dense and compact with a low pore volume. The Manorhamilton and Clara Hill yellow are slightly less dense and more porous.

The results (table 2) revealed that the Drumbane sandstone is a dense, low porosity rock; and agree with the petrographic analysis evidencing the rust (ferruginous) stone as less dense with a more open, coarser pore structure. Therefore, a clear relationship can be established between increasing porosity and decreasing density as the iron content rises: the grey rock is denser and less porous while the ferruginous (rust) quarry sandstone with abundant iron is more porous and less dense (table 2). A similar relationship is evident in the Clara Hill sandstone.

With the exception of the dark grey variety, the Killaloe sandstone is a dense, low porosity rock. This agrees with the petrographic results evidencing that the majority of the stone is dense and compact with low pore volume, but the darker varieties are more weakly cemented and contain larger pores.

Table 2. Mass properties of sandstones.

Sandstone	variety	Porosity %	Density- kg/m <sup>3</sup>
Drumbane	grey-siliceous	3.6	2561
	ochre-ferruginous	8	2323
Manorhamilton		11.0	2329
Killaloe	buff	2.3	2550
	green/grey	1.5	2660
	ochre	2.7	2543
	dark grey	8.3	2436
Clara Hill	grey	4.7	2481
	yellow	15	2188

### 3.3 Capillary absorption and evaporation

As expected for materials with the range of porosity and pore characteristics above, capillary suction is rather low, and there is a significant reduction in the moisture transport in the 2nd 24 hours (Figure 9). The results evidenced that, in general, capillary absorption relates well to porosity therefore, the pore system of the sandstones is well interconnected and efficient in transporting fluids. The Manorhamilton stone has a slightly lower capillarity than expected from its porosity therefore, its

pore system may not be as well connected as the other sandstones, a lower early evaporation rate (Figure 10) reinforces the inferior pore connection. The results agree with the porosity and density results as the sandstones with lower density and higher porosity show a greater capillary suction (Manorhamilton and Clara Hill yellow and Drumbane ferruginous variety).

The ferruginous Drumbane Sandstone (Dfer in Figure 9) is substantially more permeable than the siliceous rock: the pore structure of the less dense, ferruginous rock facilitated the movement of up to 2/3 more moisture by capillary absorption and almost twice as much by evaporation (Figure 10), compared to the siliceous type.

The Killaloe sandstone displays a low capillary absorption and evaporation, except for the dark grey porous material which shows greater values. The ochre variety has higher capillarity and evaporation and similar porosity than the other varieties; its pores are therefore narrower facilitating greater capillary movement.

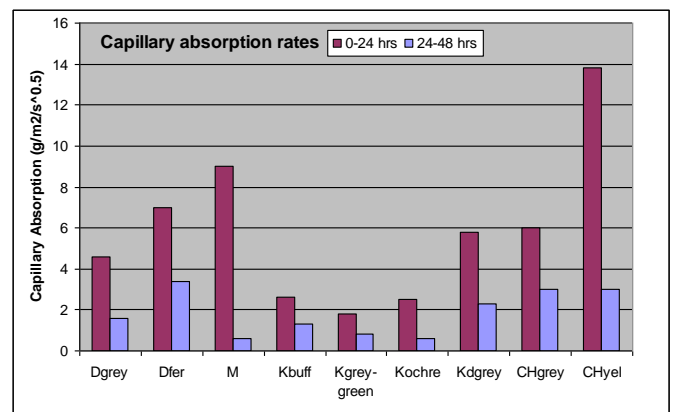


Figure 9. Capillary absorption of the sandstones.

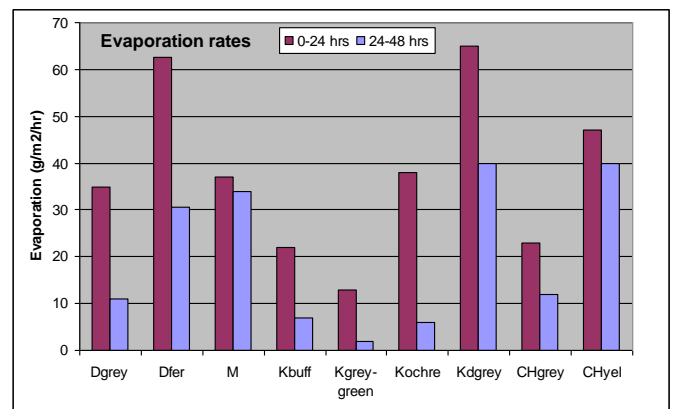


Figure 10. Evaporation rates of the sandstones.

### 3.4 Compressive strength and Elastic Modulus

The sandstones investigated are strong and stiff materials of brittle behaviour, typical shear failure and high surface hardness. Their mechanical properties compare well with those of granite and other strong, durable igneous rocks and agree with previous results evidencing the sandstones as

Sandstone	variety	Compressive strength N/mm <sup>2</sup>	E GPa	Hardness N/mm <sup>2</sup>
Drumbane	grey-siliceous	121	32	130±13
	ochre-ferruginous	70	26	76±8
Manorhamilton		105	36	90±8
Killaloe	buff	156	47	170±17
	green/grey	108	32	130±13
	ochre	-	-	130±13
	dark grey	-	-	120±12
Clara Hill	grey	62	15	80±8
	yellow	50	13	-

dense, compact materials of low pore volume and permeability.

The Drumbane (siliceous variety), Manorhamilton and Killaloe sandstones are the strongest and stiffest rocks, their strength and stiffness is well over that of typical Portland cement concrete and engineering grade brick. The Clara Hill is the weakest and less stiff sandstone however its strength and stiffness are well over those of most conventional building units, closer to engineering grade materials.

Most of the crushed samples displayed near perfect shear cones. However, the stiffest specimens were more brittle and displayed failure along steeper planes. The values showed acceptable coefficient of variation. In the Drumbane sandstone, strength was on average 17 % lower when the axial load was applied along the bedding. The results agree with Wilkinson [9] who reports the force required to crush a 1” cube of ferruginous Drumbane stone as 10290 lbs, which is equivalent to a strength of approximately 84 N/mm<sup>2</sup>. The siliceous variety is significantly stronger, however as stiff, as the ferruginous one. This agrees with previous results evidencing the ferruginous variety as less dense, with greater porosity and permeability due to a more open and coarser pore structure. Therefore, there is an inverse relationship between compressive strength and iron content. This relationship is maintained in the Clara Hill sandstone. The surface hardness values correlate well with the strength measured. Extrapolation outside the range of the manufacturer’s calibration chart was required to correlate the hardness readings to compressive strength, as a result, as indicated, it can be an approximate 10% error on the results (table 4).

The Manorhamilton sandstone is slightly less dense and more porous than the other sandstones and yet it is as strong and often stiffer. This may be related to the lower interconnections of its pore system previously evidenced resulting in a stronger microstructure.

The compressive strength of the Killaloe sandstone is very high ranging from 108 to 156N/mm<sup>2</sup>. The rock is a stiff material with a modulus of elasticity ranging from 13-15 GPa. Similarly to the other sandstones, the crushed samples exhibited shear failure, some brittle specimens displaying high angle planes of failure. The ochre and dark grey varieties were not tested in compression however, the strength obtained with the hardness tests agrees with the crushing strength of the other specimens. The buff coloured variety is stronger however as stiff as other types (standard deviation of 1.8 GPa).

Table 4. Mechanical properties of sandstones. All shear failure. E-Modulus of elasticity.

#### 4 CONCLUSION

All sandstones investigated are siliceous. They are dense, strong and stiff materials of low porosity and permeability, brittle behaviour and typical shear failure. Their property values compare well to those of granite and other strong, durable igneous rocks. Therefore, in sound condition, they are compatible with mortars of medium and high hydraulicity; and their siliceous composition is compatible with TEOS consolidants which would allow chemical bonding of the new silicates to the quartz forming the pore walls.

The Drumbane (siliceous variety), Manorhamilton and Killaloe sandstones are the strongest and stiffest rocks, their strength and stiffness is well over that of typical Portland cement concrete and engineering grade brick. The Clara Hill is the weakest and less stiff sandstone however, its strength and stiffness are well over those of most conventional building units, closer to engineering grade materials. The Manorhamilton sandstone is slightly less dense and more porous than the other sandstones and yet it is as strong and often stiffer, this may be related to the limited interconnection of its pore system resulting in a stronger microstructure.

In the most ferruginous rocks (Drumbane and Clara Hill sandstones), there is an inverse relationship between compressive strength/density and iron content: as the iron cement (haematite) lowers, the rocks become denser and mechanically stronger as well as less porous and permeable.

Two clear varieties of the Drumbane sandstone can be evidenced with the naked eye in the quarry just by the colour (grey and rust). The grey variety is more siliceous, significantly denser and stronger, with lower permeability and porosity than the rust one. The rust (ferruginous) variety contains significant iron oxides (mainly haematite) which are responsible for the colour change. This rock is mechanically weaker and less dense, with greater porosity and permeability due to a more open and coarser pore structure.

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