# Lithofacies and petrophysical properties of Portland Base Bed and Portland Whit Bed limestone as related to durability

C.W. Dubelaar[1], S. Engering[2], R.P.J. van Hees[3,4], R. Koch[5] & H.-G. Lorenz[5]

[1]  Netherlands Institute of Applied Geoscience - TNO, PO Box 80015, 3508 TA Utrecht, The Netherlands
[2]  Building Stone Consultant, Treeton, S60 5QR United Kingdom
[3]  TNO Building & Construction Research, Delft, The Netherlands
[4]  Delft University of Technology, Faculty of Architecture, Delft, The Netherlands
[5]   Institute of Paleontology, University of Erlangen-Nürnberg, Germany

This study focuses on the differences in lithofacies and petrophysical properties of Base Bed and Whit Bed Portland limestone and the presumed relationships between these characteristics and the durability of this building stone. As Portland limestone probably will be used as a stone for several restoration projects in the Netherlands in the near future, it is of great importance to know the weathering behaviour, especially its resistance against freeze/thaw decay. Samples of Portland limestone were analyzed by means of thin section microscopy, X-Ray fluorescence spectroscopy, and measurements of petrophysical properties such as watersaturation, porosity, permeability and specific surface area. Distribution of pore throat diameters were analyzed by mercury porosimetry. Results of a freeze/thaw test performed on Whit Bed limestone were also taken in account. The Whit Bed consists of a medium grained, fine to coarse bioclastic oolitic limestone (oobiosparite; oolitic grainstone). Generally the fabric is grain supported showing a large amount of open inter-particle pores. High effective porosity combined with high permeability (1000 - 1400 milliDarcy), predominantly reflect the open interparticle porosity. The Base Bed is also a coarse bioclastic oolitic grainstone, but the oolitic fabric shows a tighter, matrix-rich compacted texture. Samples from the Base Bed show differences in primary matrix contents compared to the Whit Bed and differences in diagenesis, resulting in different physical properties. For example, a lower effective porosity (15.11 - 15.99 vol.%) and a lower permeability (35.0 - 80.1 milliDarcy). It is concluded that a thorough study of lithofacies (especially microfacies) and analysis of microporosity reveal basic data for selecting the most durable type of limestone. In this particular case, using only samples from one quarry, the Whit Bed samples are thought to be the most durable ones.

Key words: Building stone, Portland limestone, Base Bed, Whit Bed, lithofacies, microfacies, durability, freeze/thaw decay, microscopy, mercury intrusion porosimetry

# 1　Introduction

Limestones from the Isle of Portland have been extracted for use in buildings since Roman times, but became a popular building material in the United Kingdom during the past three hundred and fifty years. Portland limestone was used extensively by Sir Christopher Wren for St. Pauls' cathedral (Fig.1) and for numerous other churches that he rebuilt after the Great Fire in London in 1666. The appropriate building stones, the so-called Freestone series, are derived from three main beds, from bottom to top in the sequence: the Base Bed, the Whit Bed and The Roach (Edmunds & Schaffer 1932, Arkell 1933, Townson 1971, see Fig. 2). Based on the long term experience of using Portland Limestone in the UK, it has become clear that the most durable stones come from the Whit Bed (Yates & Butlin 1996). The Roach stone can also be very durable but is less suitable for carving because of the greater amount of large fossils. Its use in Dorset breakwaters, dating from the nineteenth century, showed that the Roach stone performed adequately (Clark 1988).
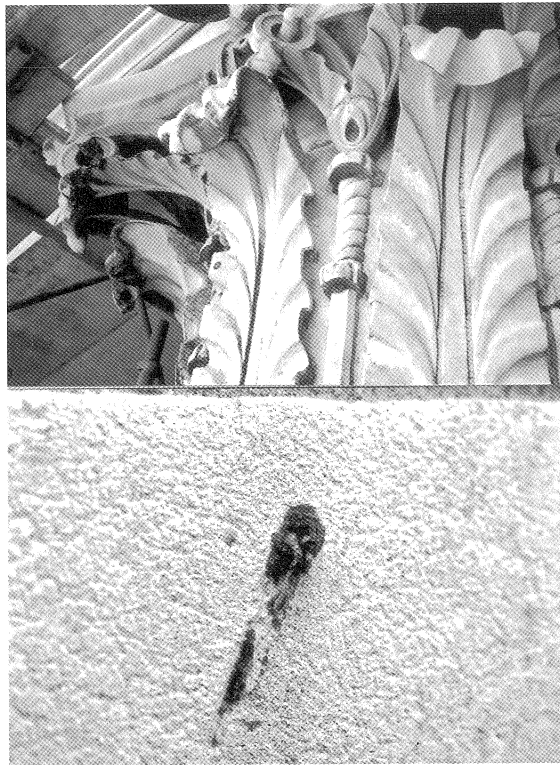


*Fig. 1. Capital at St. Pauls' Cathedral made from Portland limestone showing still sharp edges (above). Detail of Portland Whit Bed with a shell standing in low relief because of erosion of 2 mm of limestone during the past 330 years (below). Photographs January, 2000.*

## 1.1　*Aim and scope of the study*

So far, the petrophysical properties of Base Bed and Whit Bed and the presumed relationships between these characteristics and durability have not been studied in detail. As Portland limestone will be used as a stone for several restoration projects in the Netherlands in the near future, it is of great importance to know the weathering behaviour and to predict, if possible, the durability of

Portland limestone. Climate in the Netherlands is temperate humid, and precipitation during autumn and winter is considerably high (over 400 mm), with many natural freeze/thaw cycles. Therefore, besides other criteria for selecting Portland limestone, it is of great importance to use the building stones with a high resistance against freeze/thaw decay. The experience in The Netherlands clearly stresses the need of applying the appropriate building material. For example, the damage by frost action to the travertine cladding and sculptures, and to the bricks in the core of the National Monument in Amsterdam, after only forty years of exposure, clearly showed that the applied materials were not the most durable ones (Dubelaar et al. 1997, Van Hees & Larbi 2000).
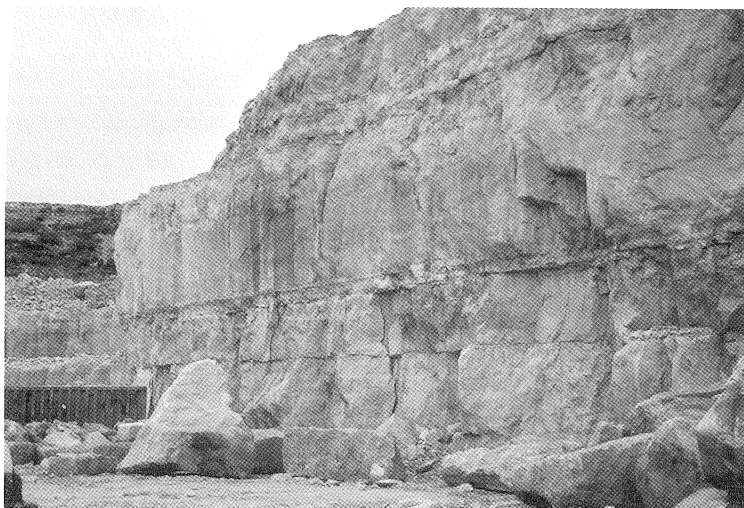


Fig. 2. Succession in Bowers Quarry, Portland Island. Base Bed overlain by a few thin layers with a chalky structure, known as the Curf, and a 3 m thick massive layer of Whit Bed. Photograph January, 2000.

## 2 Methods and investigations

Within the framework of the research of selecting the stones for the restoration of St. Johns' Cathedral in 's-Hertogenbosch, samples from three different quarries were available (Dubelaar et al. 2003). In this study we concentrate on a series of specimen taken from two stratigraphic sections in Bowers Quarry (Fig. 2). The analytical techniques included thin section microscopy, X-Ray Fluorescence spectroscopy, and measurements of petrophysical properties such as watersaturation, porosity, permeability and specific surface area. Distribution of porethroat diameters were analyzed by mercury porosimetry. Results of a freeze/thaw test performed on Whit Bed limestone were also taken in account.

## 3 Lithofacies and petrophysical properties

### 3.1 Stratigraphy and mineralogy
The Freestone succession in Bowers Quarry consists of Portland Whit Bed, locally subdivided into

223

two layers (Lynham Whit Bed and Saunders Whit Bed, thickness 2 - 3 meter), underlain by one or two layers of Portland Basebed (thickness 1 - 2 meter). Between the Base Bed and Lynham Whit Bed a thin bed (thickness 0.2 - 0.4 meter) occurs, called the Curf (Fig. 2), which has a chalky structure and is not used as a building stone.

X-Ray Fluorescence spectroscopy analysis showed that the carbonate content of the Whit Bed samples is about 97 - 98 wt.%. Silica content is small (1 – 2 wt.%) and the stone is almost free of clay and iron minerals (Dubelaar et al. 2003). Samples of the Base Bed were not analyzed by XRF, but the chemistry is thought to be similar to that of the Whit Bed layers. The lack of Fe-(hydr)oxides gives the Portland limestone its very white appearance.

### 3.2 Lithofacies and diagenetic history

The Whit Bed consists of a medium grained, fine to coarse bioclastic oolitic limestone (oobiosparite; oolitic grainstone). The average grain diameter is about 0.3 mm. The ooids and biogenic allochems are surrounded by traces of altered thin rims of isopachous marine cements and commonly syntaxial overgrowth cements on echinoid fragments, providing protection from compaction and thus preserving the primary fabric. Furthermore, minor amounts of granular and scalenohedral calcite cements occur. Between the Lynham Whit Bed (BLW) and Saunders Whit Bed (BSW) some small differences exist in the proportion of the shell fragments, the amount of matrix-relics and the amount of cement between the ooid grains. Generally the fabric is grain-supported showing a large amount of open inter-particle pores (Fig. 3). The slight differences in the amount of cement result in somewhat higher values of the total porosity of the Saunders Whit Bed samples (Table 1). High effective porosity combined with high permeability (1000 - 1400 milliDarcy), predominantly reflect the open interparticle porosity.
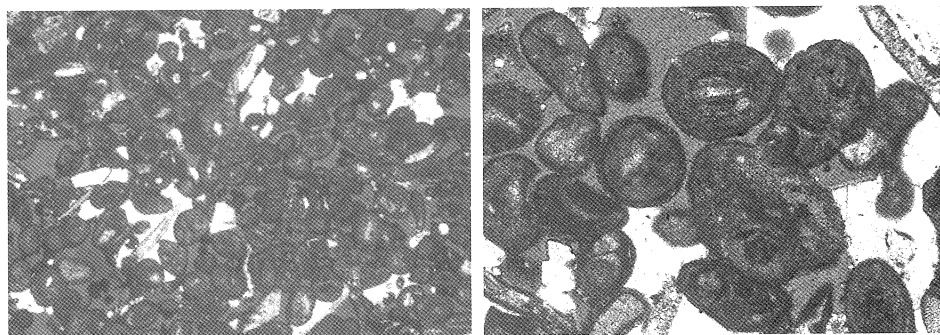


Fig. 3. (left) Microphotograph of Lynham Whit Bed (BLW), showing the large inter-particle pores in the medium grained oolitic grainstone. (right) Microphotograph showing the concentric built up of ooid grains and shell fragments (white) in detail. Base of right photograph is about 1.5 mm.
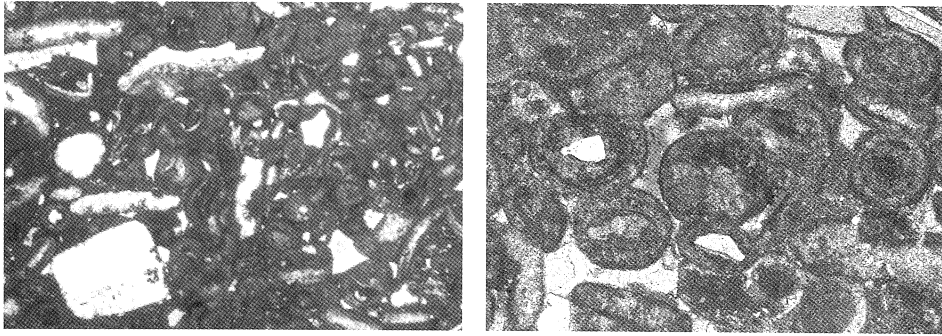
*Fig. 4. ( left) Microphotograph of Base Bed (BBB), showing the tight, more compacted fabric of the coarse oolitic grainstone. White parts are large shell and echinoid fragments. (right) Microphotograph showing a detail of the compacted fabric of the Base Bed. Base of right photograph is about 1.5 mm.*

The Base Bed is also a coarse bioclastic oolitic grainstone, but the oolitic fabric shows a tighter, matrix-rich compacted texture (Fig. 4). Samples from the Base Bed show differences in primary matrix contents compared to the Whit Bed and differences in diagenesis, resulting in different physical properties,for example, the lower effective porosity (15.32 - 16.34 vol.%) and a much lower permeability (35.0 - 80.1 milliDarcy). The oolitic grainstones are lacking early cement seams around the grains. Thus, compaction features are abundant, resulting in a very tight fabric with a high content of micritic matrix. The compaction of grains (fitting of grains) was probably induced by an early diagenetic freshwater influx. Tiny quartz grains occasionly form cores of the ooids. Locally, silica overgrowth occurs; the silica may have been derived from terrestrial sandy sediments.

### 3.4 Porosity and permeability

From the data in Table 1, it is obvious that porosity and permeability of the Base Bed samples (BBB) differ substantially from the values of the Whit Bed samples. Especially the lower permeability of the BBB samples is assumed to be a negative factor in the resistance against freeze/thaw conditions. Saturation factor S is also slightly higher in the BBB samples.

During prolonged periods of rain in the autumn and winter, the stones will get soaked with water. The stones will not dry completely because of high Relative Humidity in the Netherlands during most of the winterseason. The capillary transport (capillary suction) will draw the water molecules into the finest capillary pores. When freezing starts the frozen water will place the stones under pressure, forming internal microcracks which eventually result in macrocracks and scaling.

### 3.5 Microporosity and durability

Pore throat diameters of a few samples of Whit Bed and Base Bed were measured by mercury porosimetry. The analyses were carried out at the Institute of Paleontology, University of Erlangen-Nürnberg. The underlying principle to the method is that the pressure required to force the mercury into an empty pore is dependent upon the size of a pore throat, the connections between the pores. Distribution of pore throat diameters from two samples, which are representative for Lynham Whit Bed and Base Bed, respectively, are depicted in Fig. 5.

*Table 1. Petrophysical properties of Base Bed (BBB), Lynham Whit Bed (LWB) and Saunders Whit (Bed BSW) samples.*
*Series: a – vertical to the bedding, b – parallel to the bedding.*

| sample | water saturation (air) [weight %] | water saturation (vacuum) [weight%] | saturation factor S | effective por. [vol. %] | dead por. [vol. %] | total por. [vol. %] | porosity (mercury porosimetry) (range 0.0074-500 µm) | permeability [mD] | specific sur face area [m²/g] |
|---|---|---|---|---|---|---|---|---|---|
| BSW 63532-1a | 7.43 | 11.44 | 0.65 | 23.63 | 0.20 | 23.83 | 23.97 | 1079.7 | 0.61 |
| BSW 63532-1b | 7.54 | 12.03 | 0.63 | 24.48 | 0.51 | 24.99 | 23.97 | 932.2 | 0.61 |
| BSW 63532-2a | 8.01 | 12.58 | 0.64 | 25.37 | 0.25 | 25.62 | 21.37 | 732.8 | 0.79 |
| BSW 63532-2b | 7.27 | 11.71 | 0.62 | 24.05 | 0.16 | 24.21 | 21.37 | 844.0 | 0.79 |
| BLW 64280-1a | 7.17 | 11.12 | 0.65 | 23.15 | 0.05 | 23.20 | 21.96 | 1436.7 | 0.88 |
| BLW 64280-1b | 6.99 | 10.85 | 0.64 | 22.71 | 0.09 | 22.80 | 21.96 | 926.7 | 0.88 |
| BLW 64280-2a | 7.14 | 11.11 | 0.64 | 23.14 | 0.01 | 23.15 | 22.39 | 1258.7 | 0.81 |
| BLW 64280-2b | 7.05 | 11.17 | 0.63 | 23.22 | 0.07 | 23.29 | 22.39 | 1090.5 | 0.81 |
| BLW 64280-3a | 7.05 | 10.92 | 0.65 | 22.83 | 0.07 | 22.89 | 21.93 | 1442.4 | 0.85 |
| BLW 64280-3b | 6.89 | 10.83 | 0.64 | 22.68 | 0.06 | 22.74 | 21.93 | 1459.8 | 0.85 |
| BLW 64281-1a | 6.53 | 10.46 | 0.62 | 22.08 | 0.01 | 22.08 | 21.08 | 979.0 | 0.66 |
| BLW 64281-1b | 6.59 | 10.55 | 0.62 | 22.23 | 0.04 | 22.27 | 21.08 | 1105.7 | 0.66 |
| BLW 64281-2a | 6.95 | 10.47 | 0.66 | 22.10 | 0.06 | 22.15 | 22.11 | 754.5 | 1.23 |
| BLW 64281-2b | 6.81 | 10.21 | 0.67 | 21.67 | 0.04 | 21.71 | 22.11 | 569.5 | 1.23 |
| BLW 64281-3a | 6.50 | 10.18 | 0.64 | 21.60 | 0.09 | 21.69 | 21.32 | 1084.0 | 0.79 |
| BLW 64281-3b | 6.46 | 10.10 | 0.64 | 21.47 | 0.09 | 21.55 | 21.32 | 789.9 | 0.79 |
| BBB 18492-1a | 4.64 | 6.59 | 0.70 | 15.11 | 0.20 | 15.32 | 14.84 | 13.8 | 1.09 |
| BBB 18492-1b | 4.94 | 7.14 | 0.69 | 16.17 | 0.17 | 16.34 | 14.84 | 35.0 | 1.09 |
| BBB 18492-2a | 4.77 | 7.04 | 0.68 | 15.99 | 0.20 | 16.18 | 13.93 | 18.4 | 1.22 |
| BBB 18492-2b | 4.87 | 6.98 | 0.70 | 15.85 | 0.22 | 16.08 | 13.93 | 80.1 | 1.22 |

# Distribution of pore throat diameters

## HG 117N, Portland Limestone, BLW 64281-3

percentage of total measured pore volume

equivalent pore throat diameter [μm]
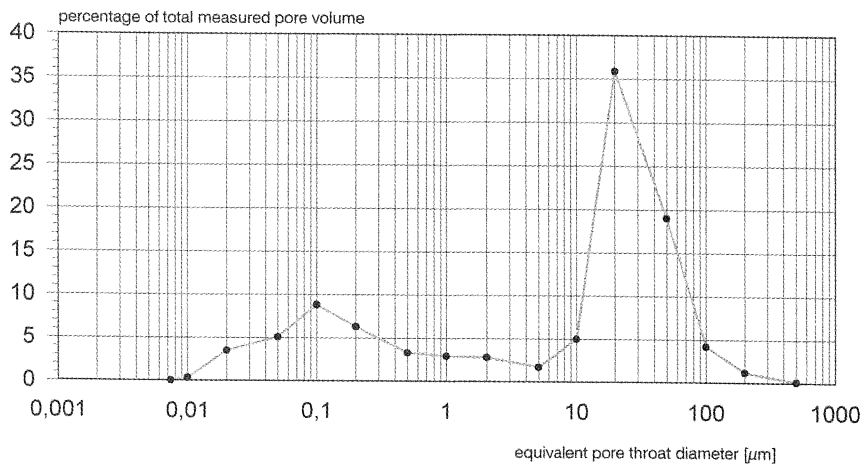
total measured pore volume: 21,32 % (range 0,0074-500 μm)

# Distribution of pore throat diameters

## HG 122N, Portland Limestone, BBB 18492-2

percentage of total measured pore volume

equivalent pore throat diameter [μm]
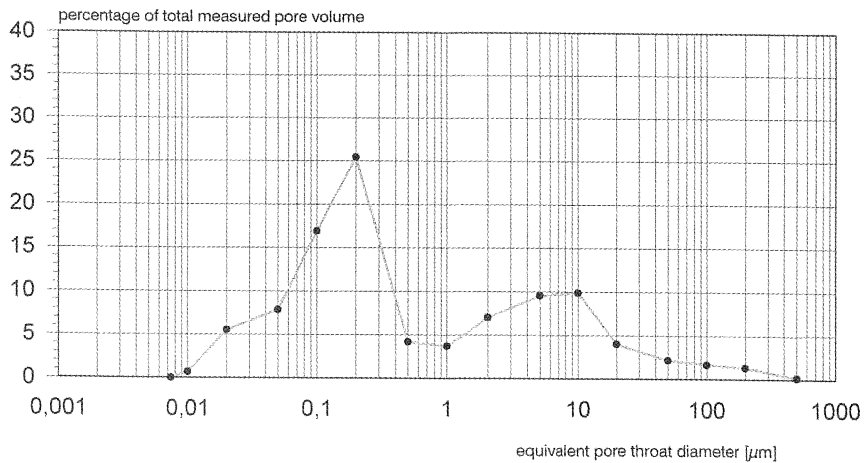
total measured pore volume: 13,93 % (range 0,0074-500 μm)

Fig. 5. Distribution of pore throat diameters of samples BLW and BBB. For explanation, see text.

The maximum of the pore throat diameter in the BLW sample is in the range 10 - 100 µm, while the maximum of the BBB sample is in the range 0.1 - 1.0 µm. A high value of fine, capillary pores (micropores < 1 µm) allows a fluid to be absorbed by capillary action. Dimension stones with a high proportion of fine pores generally are less durable than stones that have mainly coarse pores (BRE 1997).

### 3.6  Freeze / thaw test

A direct test of durability, subjecting the stone to conditions comparable to that in the outdoor environment on the continent, is a freeze/thaw test. The frost resistance of specimens ranging in size 10 x 10 x 10 cm were determined according to the Dutch Standard NEN 2872. Dubelaar et al. (2003) reported the testing of specimens Portland Whit Bed limestone which showed that samples with a high microporosity (pores < 1 µm making up more than 85 % of the total pore volume) are more prone to decay than the samples with microporosity < 50 %, but the differences in behaviour in the test are rather small.

Comparing these data with the distribution of pore throat diameters of the samples Lynham Whit Bed (microporosity about 30 %) and Base Bed (microporosity about 75 %; Figure 5), it may be assumed that the Base Bed samples are a little less durable than the Lynham Whit Bed samples.

It must be stressed that durability in this study is restricted to the expected behaviour of the samples under freeze/thaw conditions. Other weathering processes, e.g. those related to air pollution, which may play a distinctive role in limestone decay in an industrial area, are not dealt with in this research.

## 4  Conclusions

It is concluded that differences in lithofacies of samples Base Bed (BBB) and Whit Bed (BLW: Lynham Whit Bed & BSW: Saunders Whit Bed) Portland limestone from one quarry are reflected in differences in petrophysical properties. Samples from the Whit Bed are fine to coarse bioclastic oolitic grainstones with large open interparticle pores, whereas Base Bed samples are bioclastic oolitic grainstones showing a more tight, matrix-rich compacted structure. Base Bed samples show lower effective porosity (15.11 – 15.99 vol.%) and lower permeability values (35.0 – 80.1 milliDarcy) than Whit Bed samples (21.47 – 25.37 vol. % and 569.5 –1459.8 milliDarcy, respectively). Combining this data with the differences in microporosity (Base Bed samples about 75 % and Lynham Whit Bed samples about 30 %), it can be assumed that Base Bed samples are a little less durable than LynhamWhit Bed samples.

Considering the nearly equal values of the petrophysical properties of the samples from Saunders Whit Bed and Lynham Whit Bed, it is thought that no differences in durability exist between these two Whit Bed layers.

# Acknowledgements

# References

- Arkell, W.J., 1933. The Jurassic System. Oxford University Press, Oxford.
- BRE, 1997. Selecting natural building stones. Digest 420.
- Clark, A.R., 1988. The use of Portland Stone rock armour in coastal protection and sea defence works. Quarterly Journal of Engineering Geology 21:113-136.
- Dubelaar, C.W., Koch, R. & Lorenz, H-G., 1997. Weathering of travertine in a temperate humid climate, National Monument, Amsterdam, Netherlands. In: Koukis, G., ed., Proceedings of the International Symposium on Engineering Geology and the Environment, Athens, 3135-3141.
- Dubelaar, C.W., Engering, S., Koch, R., Lorenz , H.-G. & Van Hees, R.P.J., 2003. Lithofacies characteristics and physical properties as related to the durability of Portland Whitbed Limestone (St. Johns Cathedral,'s-Hertogenbosch, The Netherlands. In: Yuzer, E., Ergin, H. & Tugrul, A., eds. Proceedings of the International Symposium on Industrial Minerals and Building Stones, Istanbul, 539-544.
- Edmunds, F.H. & Schaffer, R.J., 1932. Portland Stone, its geology and properties as a building stone. Proceedings of the Geologists' Association 43:225-240.
- Hees, R.P.J. van & Larbi, J., 2000. The conservation of the sculpture work of the National Monument in Amsterdam. In: Proceedings of the 9th International Congress on Deterioration and Conservation of Stone, Venice, 523-531.
- NEN 2872, Testing of stony materials – Determination of frost resistance. Single sided freezing in fresh water environment (May 1989).
- Townson, W.G., 1971. Facies analysis of he Portland Beds. PhD thesis, University of Oxford.
- Yates, T.J.S. & Butlin, R.N., 1996. Predicting the weathering of Portland limestone buildings. In: Smith, B.J. & Warke. P.A., eds., Processes of Urban Stone Decay, 194-204.