INTERNATIONAL BUILDING PERFORMANCE SIMULATION ASSOCIATION ENGLAND

Proceedings of BSO-V 2020
5th Building Simulation and Optimization Virtual Conference
21-22 September 2020
Loughborough, UK

Hygrothermal properties of Scottish building stone and mortar

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Abstract

Traditional solid masonry walls allow moisture transfer which determines their performance and durability but retrofitting thermal insulation risks upsetting the equilibrium within a wall. To prevent accelerated material deterioration, understanding the hygrothermal impacts of building alterations is critical for structures in exposed locations, and hygrothermal simulation software allows the impact of insulation retrofits to be assessed before a retrofit project starts and helps to avoid negative effects. However, the available software packages lack information on the material properties of Scottish masonry. This paper reports a project to contribute to a data set of material properties. Values of thermal conductivity, sorptivity or water absorption coefficient by partial immersion, water vapour permeability (dry and wet cup), hygroscopic sorption, density and porosity have been determined for the following materials: Natural hydraulic lime mortars (NHL2, NHL3.5 and NHL5) and a hot-mixed lime mortar in both the uncarbonated and carbonated states, an earth mortar, three building stones in current production (Hazeldean sandstone, Locharbriggs sandstone and Scottish Whinstone) and three building stones used historically but no longer in production (Crathes granodiorite, Craigleith sandstone and Giffnock sandstone). This is the first time such data have been brought together.

Introduction

Hygrothermal building performance simulation software such as WuFI (2020) offers the possibility of predicting the effect of a retrofit intervention on the moisture performance of masonry at the design stage (Little et al, 2015). WuFI provides a database of numerical values but there are no Scottish masonry materials in the database and a recent English report (MHCLG, 2019) giving technical guidance on the risk of moisture-induced damage in both new and retrofit construction notes that "there is currently a lack of tested or standardised material characteristics for those typically used in the UK". The objectives of this work were to determine the thermal conductivity, water vapour permeability, sorptivity/water absorption coefficient, hygroscopic sorption, density and porosity of a range of Scottish masonry materials.

Materials and specimen preparation

Mortar was mixed in the laboratory using natural hydraulic lime (NHL2, NHL3.5 and NHL5, St Astier, France) and concrete sand (1:3 by volume). Hot-mixed lime mortar and earth mortar were collected from an active work site in Dunbar. The fresh mixes were cast into 100mm cubes and 12mm thick tiles and either stored damp to protect against atmospheric carbonation or carbonated in a controlled environment chamber at 20°C, 60% relative humidity (rh) and 600ppm CO_2.

Six building stones representative of Scottish masonry were selected. Of those in current production, Hazeldean sandstone, Locharbriggs sandstone and Scottish whinstone were obtained from suppliers. Of those no longer available, Crathes granodiorite (obtained from a roadstone quarry) closely matches Rubislaw granite (which was widely used in Aberdeen), and Craigleith sandstone (Edinburgh) and Giffnock sandstone (Glasgow) were obtained from conservation projects in progress. The stones were cut to shape with a bench-mounted circular saw (Norton Clipper CM501) using a water-cooled diamond tipped blade. Because of the irregular shape of some of the samples it was not always possible to produce the intended three 100mm cubes and ten 90 x 120 x 12±3 mm tiles and these are noted in the results presented below.

Testing

Density

This was determined by displacement of water, measuring the weight of specimens in air and in water.

Thermal conductivity

This was determined in both the dry and saturated conditions using the Thermtest TLS-100 instrument (Thermtest inc, Fredericton, Canada) and the thermal probe method to ASTM D5334-14 (ASTM, 2014). The stone specimens were dried to constant mass at 105°C and the lime and earth mortar specimens were dried to constant mass at 50°C. The test was repeated after the specimens were saturated for a week in water at room temperature.

Water vapour permeability

This was determined by both dry cup and wet cup methods according to BS EN ISO 12572:2001 (BSI, 2001). Tiles were conditioned to 50% rh and their mean thickness measured with a digital calliper. They were sealed into cups containing either dry calcium chloride dessicant (dry cup tests) or saturated potassium nitrate solution (93% rh - wet cup tests), placed in a controlled environment chamber at 23°C and 50% rh and the assembly weighed at intervals (daily or longer according to the rate of mass change) over up to eight weeks.

Sorptivity and water absorption coefficient

This was determined gravimetrically according to BS EN ISO 15148:2002 (BSI, 2002) by immersing specimens to a depth of 2mm in water and weighing at intervals of 1, 4, 9, 16, 25, 36 and 64. minutes.

Hygroscopic sorption

The moisture absorption and desorption curves were determined according to BS EN ISO 12571:2013 (BSI, 2013) by exposing 20-50g fragments of each material to the constant relative humidity atmosphere in sealed containers containing saturated salt solutions. Fragments were weighed to constant mass (typically every day up to one week) after exposure successively to relative humidities of 33% ($MgCl_2$), 53% ($Mg(NO_3)_2$), 75% (NaCl), 85% (KCl) and 93% (KNO_3), and 100% (water).

Porosity

Porosity and pore size distribution were determined by mercury intrusion in a Quantachrome PoreMaster33 instrument, using a sample cell of diameter 8 mm × 20 mm and capillary volume of 0.5 ml, with 33000 psi final pressure, on a single fragment of each material of mass approximately 2g.

Results

Consideration of confidence intervals

Using between three and five replicated measurements enables an indication of the experimental error associated with the values of each parameter to be calculated from the sum of the squares of the differences between each measurement and the mean of the replicate measurements for that material. The mean of all the sums of squares so calculated gives an error variance, from which the standard error is the square root. Multiplying the standard error by 1.64 leads to the 90% confidence interval given in the tables below.

Density

Table 1 summarises the density of each material in the oven-dry (ρ_0) and saturated (ρ_{sat}) conditions, together with the moisture content by volume (θ_{sat}) at saturation. The earth mortar specimens disintegrated on contact with water so the saturated density and the moisture content at saturation could not be determined.

The dry densities cover a 1.65-fold range from the low density lime mortars to the high density Scottish whinstone, with the sandstones grouped in between. As would be expected, the saturated moisture contents show the reverse order with whinstone the least absorbent and uncarbonated lime mortar the most absorbent.

Thermal conductivity

Table 2 summarises the thermal conductivity of each material in the oven-dry (λ_0) and saturated (λ_{sat}) conditions. The earth mortar specimens disintegrated on contact with water so the saturated thermal conductivity and the moisture content at saturation could not be determined.

Table 1: Dry and saturated density (means of 3 specimens: ±25 kg/m³)

Material	ρ_0 (kg/m³)	ρ_{sat} (kg/m³)	θ_{sat} (m³/m³)
NHL2 mortar uncarb	1911	2110	0.20
NHL2 mortar carb	1937	2121	0.18
NHL3.5 mortr uncarb	1811	1989	0.18
NHL3.5 mortar carb	1806	1992	0.19
NHL5 mortar uncarb	1949	2148	0.20
NHL5 mortar carb	1971	2166	0.20
Hot-mix mortar unc	1762	1941	0.36
Hot-mix mortar carb	1866	2008	0.31
Earth mortar	2002	-	-
Hazeldean sandstone	2273	2300	0.097
Locharbriggs sandst	2192	2283	0.14
Craigleith sandstone	2453	2489	0.045
Giffnock sandstone	2208	2291	0.13
Crathes granodiorite	2654	2658	0.006
Scottish whinstone	2919	2925	0.006

Table 2: Dry and saturated thermal conductivity (means of 3 specimens: ±0.7 Wm/K)

Material	λ_0 (Wm/K)	λ_{sat} (Wm/K)
NHL2 mortar uncarbonated	0.71	1.16
NHL2 mortar carbonated	0.62	1.03
NHL3.5 mortar uncarb	0.73	1.30
NHL3.5 mortar carbonated	0.69	1.22
NHL5 mortar uncarbonated	0.91	1.79
NHL5 mortar carbonated	0.68	1.29
Hot-mix mortar uncarb	0.22	0.83
Hot-mix mortar carb	0.20	0.66
Earth mortar	0.22	-
Hazeldean sandstone	1.73	3.97
Locharbriggs sandstone	1.45	3.36
Craigleith sandstone	1.71	4.23
Giffnock sandstone	1.07	4.15
Crathes granodiorite	2.13	2.77
Scottish whinstone	1.43	2.41

The thermal conductivity of the mortars is much lower than the stones, due to their lower density and higher porosity, in line with their higher moisture content at saturation. The thermal conductivity of all the materials is significantly higher at saturation than in the oven dry condition, as would be expected because the pores are filled with water instead of gas/vapour.

Water vapour permeability

Instead of the water vapour permeability, WuFI software uses values of the vapour diffusion resistance factor, defined as the water vapour permeability of air divided by that of the material. This indicates how much greater the vapour resistance of the material is compared to an equally thick layer of still air at the same temperature. The water vapour permeability of air under the test conditions is 1.8x10^{-10} kg/m sec Pa (BSI, 2001). Tables 3 and 4 summarise the water vapour permeability (k) and the dimensionless vapour diffusion resistance factor (μ) for each material in the dry cup and wet cup tests respectively, calculated in this way.

Table 3: Dry cup water vapour permeability (means of 5, 4 or 3** specimens: ±0.5×10^{-12} except where noted)*

Material	k (10^{-12} kg/m sec Pa)	μ
NHL2 mortar uncarb	10.3*	17.5
NHL2 mortar carb	11.9*	15.1
NHL3.5 mortar uncarb	11.1*	16.2
NHL3.5 mortar carb	11.2*	16.1
NHL5 mortar uncarb	9.6**	18.8
NHL5 mortar carb	7.1**	25.3
Hot-mix mortar uncarb	7.85*	22.9
Hot-mix mortar carb	7.84*	22.9
Earth mortar	6.23	28.9
Hazeldean sandstone	4.90	36.7
Locharbriggs sandstone	6.07	29.7
Craigleith sandstone	1.50	120
Giffnock sandstone	4.90*	36.7
Crathes granodiorite	0.17±0.06	1060
Scottish whinstone	0.13±0.06	1385

Table 4: Wet cup water vapour permeability (means of 5, 4 or 3** specimens: ±3.0×10^{-12} except where noted)*

Material	k (10^{-12} kg/m sec Pa)	μ
NHL2 mortar uncarb	19.6**	9.2
NHL2 mortar carb	23.6*	7.6
NHL3.5 mortar uncarb	22.4**	8.0
NHL3.5 mortar carb	25.7*	7.0
NHL5 mortar uncarb	20.0**	9.0
NHL5 mortar carb	16.3**	11.0
Hot-mix mortar uncarb	12.94*	13.9
Hot-mix mortar carb	13.54	13.3
Earth mortar	14.73*	12.2
Hazeldean sandstone	8.01	22.4
Locharbriggs sandstone	10.47	17.1
Craigleith sandstone	2.86**	62.8
Giffnock sandstone	10.09	17.8
Crathes granodiorite	0.36±0.14	499
Scottish whinstone	0.31±0.14	579

The wet cup tests showed higher variability as well as the well known higher water vapour permeability for all materials than in the dry cup. This difference ranges from 60-70% higher for lime mortar, Hazeldean and Locharbriggs sandstones up to a factor of 2.4 times higher for earth mortar and Scottish whinstone. The wet cup permeability covers a nearly 80-fold range and is highest for the mortars, reflecting their high porosity and open texture, and lowest for the very dense whinstone and granodiorite.

Sorptivity and water absorption coefficient

Table 5 summarises the sorptivity S and water absorption coefficient W_A for each material. The earth mortar specimens disintegrated on contact with water and could not be measured. The sorptivity and water absorption coefficient cover a 1600-fold range and are highest for the mortars, reflecting their high porosity and open texture, and lowest for the very dense whinstone and granodiorite, whose sorptivity is less than 10% that of Craigleith, the lowest sandstone.

Table 5: Sorptivity and water absorption coefficient (means of 3 specimens)

Material	S(mm/√min)	W_A(kg/m²√sec)
NHL2 mortar uncarb	1.64±0.5	0.21±0.06
NHL2 mortar carb	2.04±0.6	0.26±0.08
NHL3.5 mortar uncarb	0.89±0.25	0.11±0.03
NHL3.5 mortar carb	1.55±0.5	0.20±0.06
NHL5 mortar uncarb	0.79±0.25	0.10±0.03
NHL5 mortar carb	2.51±0.75	0.32±0.09
Hot-mix mortar uncarb	2.15±0.65	0.28±0.08
Hot-mix mortar carb	2.79±0.85	0.36±0.1
Earth mortar	-	-
Hazeldean sandstone	0.82±0.25	0.11±0.03
Locharbriggs sandstone	0.67±0.2	0.086±0.025
Craigleith sandstone	0.063±0.02	8.14x10^{-3} ±2.4 x10^{-3}
Giffnock sandstone	0.57±0.2	0.073±0.02
Crathes granodiorite	0.0085±0.0025	1.1x10^{-3} ±0.3 x10^{-3}
Scottish whinstone	0.0017±0.0005	0.22x10^{-3} ±0.06 x10^{-3}

Hygroscopic sorption

The typical set of sorption-desorption curves (Figure 1) shows visible hysteresis with the moisture content on the downcurve higher than that on the upcurve: i.e. moisture is retained in the material as the relative humidity to which it is exposed decreases.

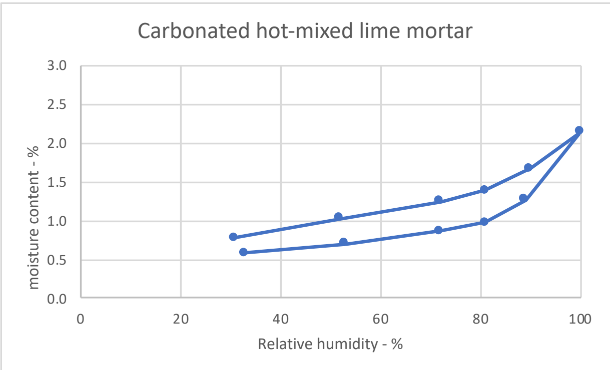

Figure 1: Sorption-desorption curves for carbonated hot-mix lime mortar.

The form of the sorption-desorption curves is the same for all materials so to facilitate comparison, Table 6 summarises the moisture contents by volume (θ_{90}) reached at 90% relative humidity on the upcurve. The results for Scottish whinstone are excluded because they make no sense: the moisture content apparently reached by water vapour sorption was much higher than by liquid saturation, suggesting an experimental problem.

Table 6: Moisture contents of each material at 90% relative humidity (means of 3 specimens: ±0.0015)

Material	θ_{90} (m³/m³)
NHL2 mortar uncarbonated	0.025
NHL2 mortar carbonated	0.015
NHL3.5 mortar uncarbonated	0.027
NHL3.5 mortar carbonated	0.015
NHL5 mortar uncarbonated	0.031
NHL5 mortar carbonated	0.014
Hot-mix mortar uncarbonated	0.026
Hot-mix mortar carbonated	0.024
Earth mortar	0.05
Hazeldean sandstone	0.0029
Locharbriggs sandstone	0.015
Craigleith sandstone	0.013
Giffnock sandstone	0.023
Crathes granodiorite	0.0031
Scottish whinstone	-

Porosity

Pore size distributions are shown in Figures 2-6, with the vertical axes showing the measured pore volumes at different scales.

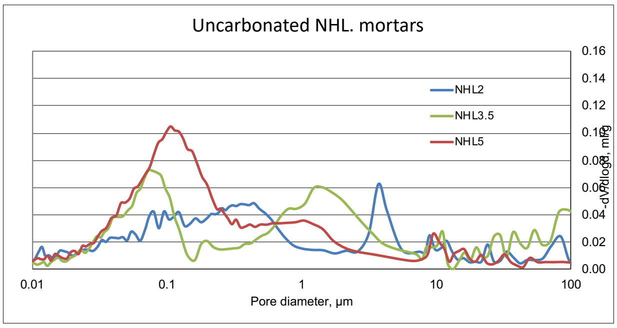

Figure 2: Pore size distributions of uncarbonated NHL mortars.

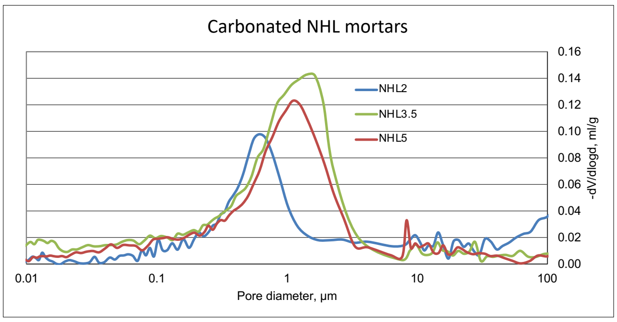

Figure 3: Pore size distributions of carbonated NHL mortars.

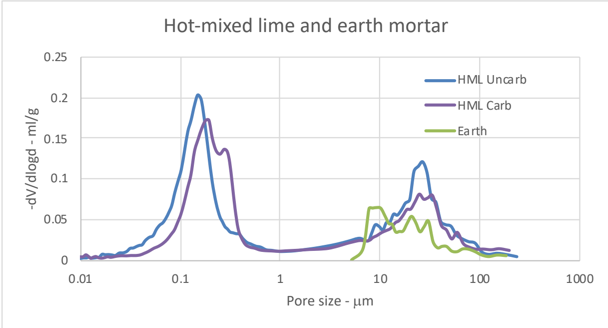

Figure 4: Pore size distributions of hot-mixed lime and earth mortars.

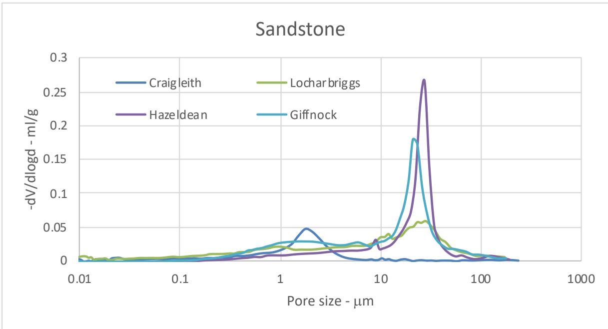

Figure 5: Pore size distributions of sandstones.

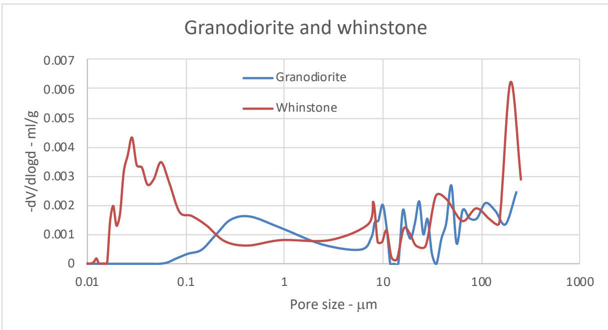

Figure 6: Pore size distributions of granodiorite and whinstone.

The uncarbonated NHL mortars show a bimodal distribution with a peak at 0.09-0.4µm and one at 1-4µm, whilst the carbonated mortars show a single peak at 0.6-1µm, all corresponding to the binder porosity. The hot-mixed lime mortars show a bimodal distribution with a peak at 0.15-0.2µm corresponding to the binder porosity and a coarser one at 30µm corresponding to the pores between sand particles. The sandstones all exhibit a well-defined main peak at 28, 25 and 20µm for Locharbriggs, Hazeldean and Giffnock, respectively, whilst in Craigleith the pores are significantly finer at 2µm. The whinstone and granodiorite have very low porosities with fine pores around 0.03 and 0.4µm and with some poorly-defined coarser pores between 10 and 150µm. The earth mortar specimen collapsed under the high intruding mercury pressure needed for the fine pores. Table 7 summarises the porosities (% by volume) of each material, somewhat arbitrarily divided into pore sizes below or above 10µm.

Table 7: Porosity (% by volume) of each material (single determination)

Material	<10µm	>10µm	Total
NHL2 mortar uncarb	13.9	5.2	19.1
NHL2 mortar carb	12.2	9.6	21.8
NHL3.5 mortr uncarb	15.3	8.7	24.0
NHL3.5 mortar carb	22.5	5.2	27.7
NHL5 mortar uncarb	20.0	4.1	24.1
NHL5 mortar carb	19.4	5.8	25.2
Hot-mix mortar unc	18.6	12.6	31.2
Hot-mix mortar carb	18.6	11.4	30.0
Earth mortar	-	8.1	(8.1)
Hazeldean sandstone	2.8	14.5	17.3
Locharbriggs sandst	6.1	9.6	15.7
Craigleith sandstone	7.3	1.0	8.3
Giffnock sandstone	6.5	14.4	20.8
Crathes granodiorite	0.5	0.6	1.1
Scottish whinstone	1.0	0.9	1.9

Discussion of data

The general trends within the measured data are consistent: more porous materials are less dense, have lower thermal conductivity, higher water absorption and higher water vapour permeability. However, to answer the question of whether the numerical values reported here are reasonable is made difficult by the absence of comprehensive data in the literature. Restricting the consideration to three generic types of material – lime mortar, sandstone and granite – and five properties – thermal conductivity, vapour diffusion resistance, water absorption coefficient, hygroscopic sorption and porosity – suggests that the data reported here are indeed broadly consistent with those reported from a range of international sources. For lime mortar, ten papers present a range of values (Table 8). For sandstone, eight papers present a range of values (Table 9). For granite, a single reference (WuFI 2020) gives values (Table 10).

Table 8: Comparison of data for lime mortar

Property	This work	Other work
Thermal conductivity (W/mK)	0.2-0.9	0.35-1.4
Vapour diffusion resistance factor	15-25	6-37
Water absorption coefficient (kg/m^2√sec)	0.28-0.36	0.06-1.2
Hygroscopic sorption (% mc by volume at 90% RH)	2.4-2.6	0.4-1.6
Total porosity %	19-31	26-49

Table 9: Comparison of data for sandstone

Property	This work	Other work
Thermal conductivity (W/mK)	1.0-1.7	1.0-3.5
Vapour diffusion resistance factor	30-120	12-150
Water absorption coefficient (kg/m^2√sec)	0.008-0.011	0.003-0.9
Hygroscopic sorption (% mc by volume at 90% RH)	0.29-2.3	0.5-2.5
Total porosity %	8-20	10-31

Table 10: Comparison of data for granite

Property	This work	Other work
Thermal conductivity (W/mK)	2.1	3.5
Vapour diffusion resistance factor	1060	60
Water absorption coefficient (kg/m^2√sec)	0.011	0.0086
Hygroscopic sorption (% mc by volume at 90% RH)	0.3	0.9
Total porosity %	1.1	0.95

Significance of the results

Clearly, the accuracy of a hygrothermal simulation depends critically on the use of the correct material properties for the building under consideration. Tables 8 and 9 show that the data for Scottish materials cover a smaller range of values than those in the literature, which suggests that the former should be used in preference. Considering only sandstone masonry, the 3.5-fold range in thermal conductivity and the 12-fold range in vapour diffusion resistance offers the modeller a wide choice of values, which could have a potentially serious influence on the simulated moisture content of a wall. As an example, this could lead to a gross over- or under-estimate of the condensation and mould growth risk in an insulated wall (Marincioni et al, 2018) but detailed consideration is beyond the scope of this paper.

Equally, Little et al (2015) point out that it is important to choose an appropriate balance between the amounts of lime mortar and dimension stone blocks within the modelled wall construction. Ashlar masonry with narrow joints between accurately fitted stones has a higher proportion of stone than in rubble masonry where the mortar is bedding more irregular shaped stones. Combined with the presence of lime mortar used as infill behind the facing stonework it is possible for the mortar to constitute as much as 40% of the volume of the wall. It is well known that lime mortar is softer, more porous, and more permeable than cement mortar, values for which appear widely in the literature. Therefore, using correct values of the hygrothermal properties of the constituent materials is vital for accurate modelling.

The data presented in this paper will make it easier for simulation of hygrothermal performance of Scottish masonry buildings.

Conclusion

Values of thermal conductivity, water vapour permeability and vapour diffusion resistance factor, by both dry cup and wet cup methods, sorptivity/water absorption coefficient, hygroscopic sorption, density and porosity have been determined for a range of building stones, natural hydraulic lime mortars and a hot-mixed lime mortar in both the uncarbonated and carbonated states, and an earth mortar. The building materials tested are all relevant to traditional masonry construction in Scotland.

Acknowledgement

Part of this work was financially supported by Historic Environment Scotland. The mercury intrusion porosimetry was performed by The University of Dundee. Gavin Spowart, Lee Masson and Graham Sorley assisted with some of the experimental work.

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