Predicting The Service-Life Of Natural Roofing Slates In A Scottish Environment

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Summary: **Natural roofing slate, the traditional roofing material of most 18th and 19th century towns and cities of Scotland has performed effectively for over 150 years. Yet in spite of their reputation for durability, many Scottish slates failed to comply with the requirements set by the British standard for roofing slate (BS680). This inability of the British and other standards to predict the performance of a slate led to this research into alternative methods of assessing quality. All national standards including the new European standard use initial water absorbency as a significant factor in determining quality of a slate. However this research shows that there is poor correlation between this factor and life expectancy and that of greater significance is the rate of increase in water absorbency during weathering. This factor was determined for a range of roofing slates by measuring water absorbency before and after experimental weathering and used as a measure of its durability. Results were calculated relative to that of a Welsh standard, which was assigned a life expectancy of 100 years. It was found that results agreed with their generally accepted reputation; all the Welsh samples have life expectancy values similar to that of the standard, the Cumbrian slates have values of over 100 years and the Spanish slates have values of approximately 50 years. To estimate longevity in absolute terms, the relationship between experimental and natural weathering was determined by comparing the corresponding rates of increase in water absorbency for slates from the same source. However because the environment is a major factor in weathering, this tentative calibration can only be applied to slates weathered in a similar climate to that of Scotland**

Keywords. slate, durability, whole life costing

1 INTRODUCTION

The durability of a roofing slate depends on many factors both inherent and external. It depends on the properties of the material such as its solubility, porosity and permeability and also on the nature of the environment particularly the climatic and anthropogenic influences. Concentrating on differences in their inherent properties the aim of this research is to devise a method of predicting ***relative*** durability of different slates based on carefully controlled experiments.

2 BACKGROUND

In an ASTM (American Society for Testing and Materials) study of roofing slates, the chemical and physical properties of used slates which had been exposed from 12 to 131 years were compared with those of freshly quarried slates from the same sources (Kessler and Sligh 1932). In this way it was found that the most significant changes due to natural weathering were loss of strength and increase in water absorbency. The study also showed that the same chemical and physical changes can be replicated experimentally by subjecting the slate to repeated cycles of wetting-and-drying. Based on this work the American standard for slates incorporated a water absorption test and a wetting-and-drying test. Given the plethora of methods used to test slates, it is significant that the new European Standard prEN12326, the British Standard BS680 and all other national standards also include water absorption and wetting-and-drying procedures.

2.1 Water absorption test

Water plays an important role in both the physical and chemical weathering processes of all natural building materials. Most national standards and the European standard prEN12326 adopt a simple immersion test whereby the amount of water absorbed by a dried slate in 48 hours at ambient temperature is measured. The Building Research Establishment (BRE) found that it took nearly a month for the amount of water absorbed by this method to reach equilibrium (Watkins 1934). However it was found possible to accelerate this process and attain equilibrium by refluxing (boiling) the sample for 48 hours. This was the method adopted by the British Standard for slate BS680. As a result of boiling the sample, instead of simply immersing it in water at ambient temperature, the figures for water absorption tested according to BS680 are usually substantially higher than those obtained using the method prescribed in the ASTM, prEN12326 and other standards.

2.2 Wetting-and-drying test

The wetting-and-drying test subjects a slate to repeated cycles of immersion in water at ambient temperature and drying in an oven at approximately 105°C. The procedures prescribed by both the British BS680 and EU prEN12326 standards for this test are essentially the same. Because the conditions closely reflect those experienced by a slate on a roof in a temperate climate, it is the method chosen to experimentally weather slates in this research. In addition changes in the properties such as increase in water absorption and loss of strength mirror those observed in naturally weathered slates.

2.3 Durability of slate

Prior to the establishment of the British Standard (BS680), BRE carried out a wide range of tests and correlated the results obtained with the reputation of the slate in question. The tests deemed to give the best correlation were then incorporated into the Standard. These were (i) the water absorption test, (ii) the acid test and (iii) the wetting-and-drying test. Slates tested were either passed or failed and no attempt was made to differentiate between different quality of slates. In the case of water absorbency, the limit was set pragmatically at 0.3% in an attempt to exclude slate of perceived poor quality. However it was recognised that this also excluded slates with a proven track record

> *…some Scottish slates of good reputation fail to meet the requirements of the (British) Standard for no other reason than that their water absorption exceed by a small margin the present limiting value of (0.3 per cent.).* Note C 330 BRE archives unpublished).

In contrast, the European standard does assign one of several grades to slates based on performance in a wide range of tests, however no attempt is made to relate these grades to their estimated longevity. The ASTM standard is the only one which estimates the life expectancy of a slate. Based on initial water absorption and depth of softening when exposed to acid vapour, this standard classifies slate into one of three grades, to each of which is assigned a corresponding life-expectancy value (Table 1).

Table 1 Life expectancy based on water absorption and depth of softening on exposure to acid vapour. ASTM data

	Modulus of Rupture		*Water Absorption*	*Depth of softening*		*Life expectancy*
	psi	*MPa*	*%*	*inch*	*mm*	*years*
Grade S_1	9000	62	<0.25	<0.002	<0.05	75-100
Grade S_2	9000	62	<0.36	<0.008	<0.20	40-75
Grade S_3	9000	62	<0.45	<0.014	<0.36	20-40

However recent research (Walsh 1999) found no relationship between **initial** water absorbency values as used in the ASTM standard and the reputation of a slate. For example a Welsh slate from Pen yr Orsedd Quarry has a water absorption of 0.24% which is higher than that of a Spanish slate from Solana de Forcadas Quarry at 0.15%. Yet a Welsh slate is expected to last over a hundred years compared to a Spanish slate which is estimated to last approximately thirty years (Maol in Builder 1995). Instead of concentrating on initial values, this research assesses the effect of weathering by measuring properties such as water absorbency at intervals during experimental weathering, using the wetting-and-drying procedure described above, in order to determining their **rate of increase**. The higher the rate of increase the more vulnerable the slate is to weathering. The profile of how a given property changes with the degree of experimental weathering is referred to as its **weathering pathway**.

3 METHODOLOGY

To assess the durability of a slate it is necessary to measure its properties before and after a period of experimental weathering. Because of the natural variation even within a single slate, measurements of changes in those properties which are assessed using destructive tests, requiring a different test piece for each measurement, are less precise than those assessed using non-destructive methods. In addition properties measured using destructive tests give only a single figure on the amount of change due to weathering and no information on how the change took place during the procedure i.e. its weathering pathway. Therefore the principal property used in assessing the effects of weathering is water absorption which is measured using a non-destructive test, enabling the same sample to be tested repeatedly at intervals during experimentally weathering. This gives a relationship between water absorption and the degree of experimental weathering on which to base a mathematical model, which can then be used to assess the durability of a slate by extrapolation to a predetermined limit. If possible this ***limit of water absorption*** should be set as that determined when the slate shows signs of failure.

Ideally the increase in water absorption due to experimental weathering would provide a characteristic profile, which could then be compared with that observed in similar slates that have been naturally weathered and the experiment thereby "calibrated". Then, given a suitable limit of water absorption, the life expectancy of the slate could be determined. To test this hypothesis, three samples were experimentally weathered by subjecting them to repeated cycles of wetting-and-drying to determine whether it was possible to detect significant changes in their properties within a reasonable timeframe and thereby establish a procedure for estimating the relative durability of different slates. The slates chosen were:

1. I/K-3 Killaloe slate from Killoran Quarry, Portroe near Nenagh, Ireland
2. W/F-8 Ffestiniog slate from Oakley Quarry, Ffestiniog, North Wales
3. S-1 Spanish slate from Solana de Forcadas Quarry, Spain

Data for naturally weathered slates from the Killoran and Oakley quarries were available enabling comparisons to be made between the effects of natural and experimental weathering. Having developed the optimum procedure for assessing durability, a range of different slates were tested, their relative durabilities estimated and where possible the results compared with their reputations.

Four test pieces, 50mm square, were cut from each slate, experimentally weathered and changes in the following properties assessed:

- Visual signs of weathering such a flaking, discoloration etc. were monitored throughout the experiment.
- Weight and thickness measurements were made at frequent intervals. To minimise the variation due to a rough surface, thickness measurements were always made at the same four locations on each of the test pieces.
- Water absorbency; two of the test pieces of each slate were tested by refluxing as prescribed by BS680 and the remaining two pieces by simple immersion as prescribed by prEN12326. The tests were repeated four times at increasing intervals until approximately 100 - 150 cycles had been carried out.

3.1 Visual signs of weathering

I/K-3 showed no visual sign of weathering throughout the experiment. Both W/F-8 and S-1 developed brown spots on the surface after a hundred cycles of wetting-and-drying but no other visual signs of weathering were observed.

3.2 Weight and thickness

No significant pattern of weight loss in the slates used in this research emerged, however supplementary work (Walsh in press) suggests that good quality slates show a small and continuous weight loss, while some poor quality samples increase in weight with weathering.

A systematic trend in thickness measurements was observed, in that all the slates tested increased in thickness during weathering. Although the actual increments were small, when analysed statistically using a Student’s t-test the changes were found to be significant. These results are shown in Table 2 and those for W/F-8 are plotted against length of weathering to show how the rate of increase in thickness increased after a hundred cycles of wetting-and-drying (Fig.1).

Table 2 Increase in thickness due to experimental weathering

Thickness (mm)	*Wetting-drying cycles*	*Mean*	*Standard deviation*	*95% Confidence Interval*	*Percentage Increase after 100 cycles*	*Student’s t-test*
I/K-3	0	5.900	0.163	±0.08		
	127	6.025	0.191	±0.09	1.7	0.06
W/F-8	0	3.688	0.096	±0.04		
	123	3.763	0.086	±0.04	1.7	0.02
	140	3.875	0.061	±0.04		
S-1	0	6.663	0.072	±0.04	3.1	
	97	6.775	0.068	±0.04		0.00

3.3 Water Absorbency

The results of water absorption tests are given in Table 3 and summarised in Figs. 2 and 3. It can be seen from these results that the slates tested showed a measurable increase in water absorption due to experimental weathering and that the results are reproducible. In general the rate of increase in absorbency increased with the degree of weathering. This is especially clear in the case of S-1, whose rate of increase in water absorbency increased significantly after an initial period of little change.

Regressional analyses of the data in Table 3 were carried out using both linear and exponential models and the closeness of fit assessed by determining the corresponding coefficients of determination. Poor fits ($R^2 \leq 0.4$) were obtained for those samples tested according to prEN12326 (Fig.2), which is interpreted as being due to the small increases in weights as compared to the imprecision inherent in weighing wet samples. To get a better fit by this method would require extending the already lengthy weathering procedure. With one exception (I/K-3) those samples measured using the BS680 method of refluxing have coefficients of determination (R^2) of approximately 0.8 indicating a good fit (Fig. 3). In the case of I/K-3 a poorer fit was obtained (R^2 =0.63) due to the very low rate of increase in absorbency. Although the coefficients of determination were approximately the same for both linear and exponential models, the latter were slightly higher in every case. This suggests that the exponential model is a truer representation of the effect of weathering, which is substantiated by other observations in both experimental and natural weathered slates.

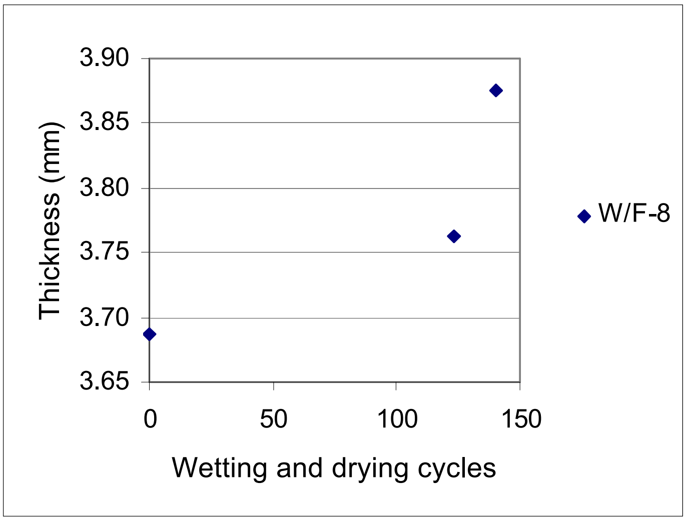

Fig.1 Increase in thickness of a slate due to experimental weathering

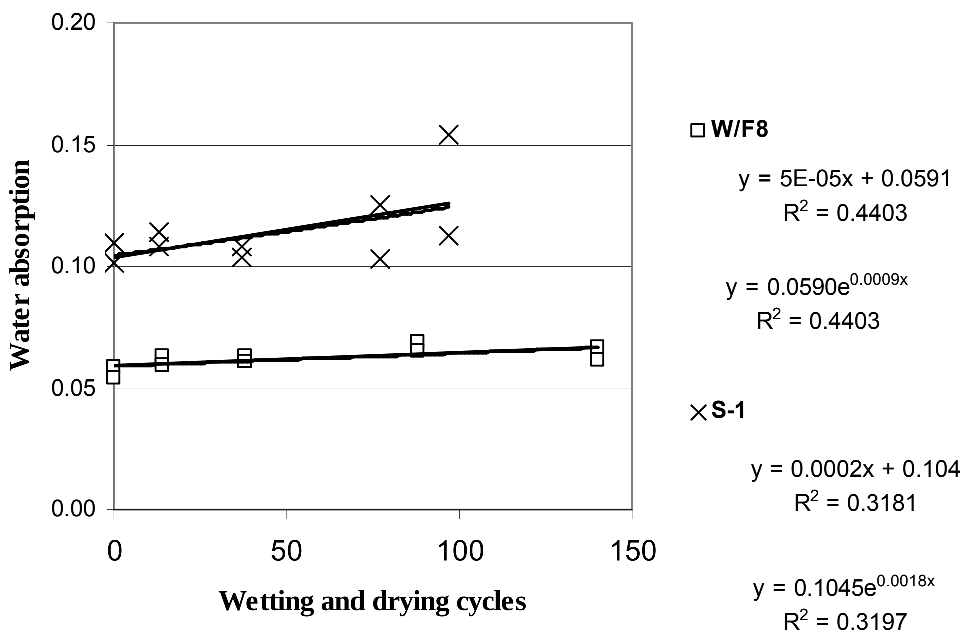

Fig. 2 Experimental weathering of Welsh and Spanish slates; water absorbency tested according to prEN12326

Table 3 Increase in water absorbency due to experimental weathering

I/K-3					
No of cycles	0	13	24	53	52
Cumulative Total	0	13	37	90	142
Water absorption (%)	0.1174	0.1177	0.1204	0.1236	0.1255
BS680	0.1212	0.1224	0.1242	0.1314	0.1331
Mean BS680	0.1193	0.1200	0.1223	0.1275	0.1293
prEN12326	0.0929	0.0959	0.0951	0.0959	0.0962
	0.0889	0.0938	0.0928	0.0917	0.0901
Mean prEN12326	0.0909	0.0948	0.0939	0.0938	0.0931
W/F8					
No of cycles	0	14	24	50	52
Cumulative Total	0	14	38	88	140
Water absorption (%)	0.0804	0.0875	0.0897	0.0997	0.1077
BS680	0.0839	0.0921	0.0943	0.1046	0.1357
Mean BS680	0.0821	0.0898	0.0920	0.1022	0.1217
prEN12326	0.0583	0.0628	0.0628	0.0692	0.0665
	0.0541	0.0595	0.0608	0.0653	0.0616
Mean prEN12326	0.0562	0.0612	0.0618	0.0673	0.0640
S-1					
No of cycles	0	13	24	40	20
Cumulative Total	0	13	37	77	97
% water absorption	0.148	0.160	0.164	0.180	0.221
BS680	0.152	0.162	0.166	0.178	0.219
Mean BS680	0.1500	0.1611	0.1654	0.1788	0.2201
prEN12326	0.1013	0.1084	0.1035	0.1033	0.1128
	0.1098	0.1143	0.1084	0.1250	0.1537
Mean prEN12326	0.1056	0.1113	0.1060	0.1141	0.1332

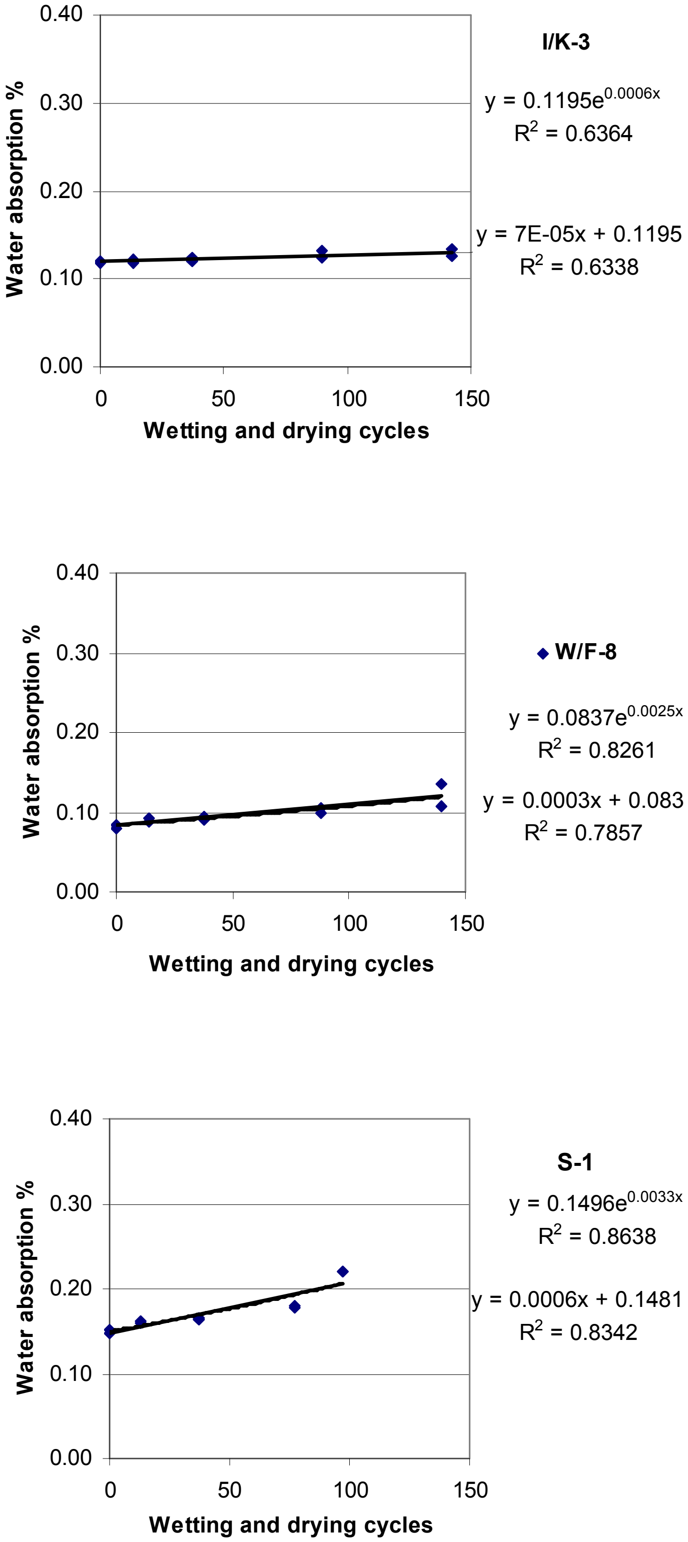

Fig. 3 Experimental weathering of slates tested according to the BS680 procedure (a) Irish, Killaloe I/K-3 (b) Welsh, Ffestiniog W/F-8 and (c) Spanish, Solana de Forcadas S-1 samples.

4 DISCUSSION

To estimate the durability of a slate, it is necessary to choose a suitable mathematical model which best represents the experimental data. The model chosen is then extrapolated in order to make predictions on performance in the future. Prior knowledge suggests that the deterioration of a slate due to weathering increases with time and that the most appropriate mathematical model is exponential. However in the last section, it was found that linear mathematical models fit the data almost as well as their exponential equivalents due to the fact that the early part of the exponential curve approximates to a straight line. Therefore it should be possible to differentiate between different quality of slates based on the differences in the gradients of their linear models. The linear regressional line for S-1 is

$$\mathbf{y = 0.0006x + 0.1481}$$

where **x** is the number of cycles of wetting-and-drying and **y** is the percentage water absorption (Fig.3c). This represents an initial water absorbency of 0.1481% and an initial rate of increase of 0.0006% per cycle. Comparing this with the linear regressional lines for I/K-3 and W/F-8 (Fig 3a and 3b), it can be seen that the rate of increase of water absorbency of the S-1 sample is approximately nine times that of I/K-3 (0.00007% per cycle) and twice that of W/F-8 (0.0003% per cycle). This demonstrates that it is possible to differentiate between different slates using initial rates of increase in water absorbency and it suggests that the order of durability is I/K-3>> W/F-8 > S-1.

However because the rate of increase in water absorbency is not constant but increases with the degree of weathering predicting the life expectancy of a slate based on an exponential model is more appropriate. This should be done by extrapolating the exponential model to a pre-determined limit, ideally one that is indicative of incipient failure. However this was not possible, even though the procedure was run for nearly a year, there was insufficient time to test any of the slates to the point of observed failure. The Welsh sample W/F-8 showed measurable deterioration after a hundred wetting-and-drying cycles, i.e. there was an increase in the rate of water absorption with time, an increase in variance of the results, as well as a visual change in that brown staining developed. However, there was nothing to suggest that failure was imminent. Hence it was not possible to define a level of water absorption indicative of failure on which to base estimates of the durability of a slate. Instead it was decided to assess the durability of the various slates relative to that of a standard. The standard chosen was the Welsh slate which was assigned a life expectancy of a hundred years, a figure that is often used in trade literature. Although new slates have a water absorption limit of <0.3%, that of used slates which are recyclable have values of <1.0%. Therefore the limit for used slates is set within this range at 0.5%. The W/F-8 regressional curve was extrapolated to determine the number of cycles necessary for the water absorption to reach this limit (Table 4). This was repeated for the other two samples and their life expectancy values were calculated *pro rata*. It was found that the Irish slate has a life expectancy of over 300 years while that of the Spanish slate is 40 – 50 years. To check the effect of the water absorption limit on the results, estimates of durability were recalculated using limits of 0.75% and 1.0%. It was found that, the actual value used within the range 0.3% to 1.0% makes little difference to the relative durability of the slate e.g. higher limits of 0.75% and 1.00% increase the relative durability of I/K-3 to 349 and 357 years respectively. Similarly the values for S-1 are increased slightly to 56 and 58 years respectively.

These results were then compared with the reputation of the slates in question, the Killaloe slate has a reputation of lasting over 200 years and several examples of such longevity was seen on the roofs of early 19th century houses in the area surrounding the Killaloe quarries. The usual figure used in the trade for Welsh slate is 100 years and that for Spanish slate expectancy of 30 years. This demonstrates that the predicted life expectancy values agree with those generally accepted by the roofing industry.

Table 4 Estimating the life expectancy of a slate relative to a standard.

New slates	*No of test cycles*	*Equations of regressional curves*	*Increase in thickness after 100 cycles (%)*	*Visual change*	*No. of cycles to 0.5%*	*Life expectancy relative to W/F-8*
I/K-3	142	$y = 0.00007x+0.1195$	1.7	No change	5436	390
		$y = 0.11956e^{0.0006x}$			2385	333
W/F-8	140	$y = 0.0003x+0.0837$	1.7	Brown stains	1390	100
		$y = 0.0837e^{0.0025x}$			715	100
S-1	97	$y = 0.0006x+0.1484$	3.1	Brown stains	587	42
		$y = 0.1496e^{0.0033x}$			366	51

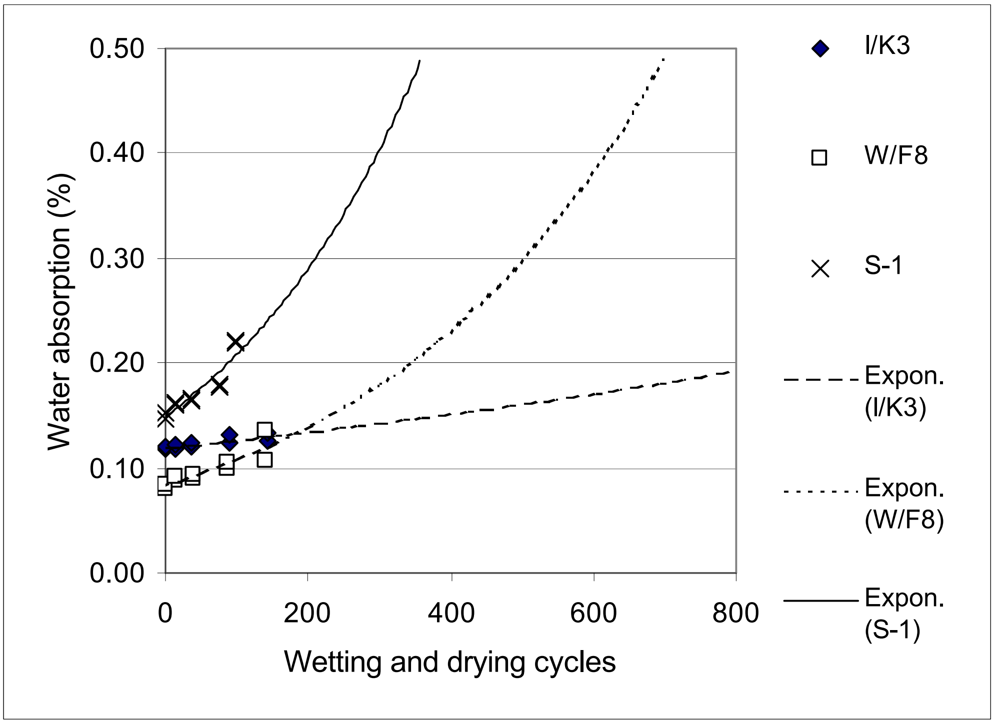

Fig. 4 Extrapolation of water absorption to a limit of 0.5% using an exponential model

Most of the above discussion is based on water absorption figures obtained using the BS 680 refluxing method. A parallel set of results was obtained according to the prEN12326 water immersion procedure. If, as reported by Watkins (1934), it takes a month of immersion in water at room temperature for the weight to stabilise, the prEN12326 test is measuring only the *rate* at which the slate absorbs water. If, again according to Watkins, weight stability is achieved by the boiling method in 48 hours, the BS 680 test measures the *total* capacity of the slate to absorb water. Both methods are valid measures of deterioration, but the BS 680 method, gives larger values and earlier signs of significant change and therefore shortens the length of time needed to evaluate a new slate.

Finally using a shortened version of the weathering procedure, extra slates were tested and estimates of their relative durability determined. It was found that the estimates for the Welsh samples were again between 100 to 125 years and those of the Spanish slates were 40-50 years, thus indicating that the results obtained by the above procedure are reproducible. In addition to the extra Welsh and Spanish samples, two Cumbrian slates were tested and found to have very high durability with estimates of over 125 years (Walsh in press). It is worth noting that the Cumbrian slates performed in accordance with their reputation for longevity even in an urban environment. In contrast these slates fail the British Standard Acid Test designed to identify those slates not suitable for use in a polluted atmosphere. However because of their proven track record in an urban environment an exception has always been made for these slates. No fresh Scottish slates were available for testing, however this work has set up a scale with which to assess the quality of a new source when it becomes available

5 CALIBRATION OF RESULTS

An attempt was made to relate the increase in water absorption in the experiment which subjected the slates to repeated cycles of wetting-and-drying, to that observed in slates which have experienced natural weathering on roofs.

A tentative calibration has been achieved based on data collected for the BRE study of weathered samples in 1948/49 (Fig. 5). A linear regression (not shown) of the few data points for naturally weathered slate samples from the *old vein* in the Ffestiniog area gave the following relationship between water absorption **y** and years of natural weathering **x.**

$$y = 0.0024x + 0.162$$

This implies an initial water absorption figure of 0.162% and an annual increase of 0.0024% per year over a hundred year period. The linear regression for the experimental weathering of a new slate from the *old vein*, gave the following relationship between the water absorption **y** and number of cycles of wetting-and-drying **x** (Fig.3b)

$$y = 0.0003x + 0.0837$$

This gives a rate of increase in water absorption of 0.0003% per cycle. By comparing these two relationships, it is possible to get a rough equivalence between natural and experimental weathering as 8 wetting-and-drying cycles per year. However the rate of increase in water absorption is not linear but increases with time so that a better comparison is based on the following exponential regressional line for natural weathering (Fig.5)

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$$y = 0.1673e^{0.0089x}$$

Comparing this with that obtained for experimental weathering (Fig. 4 and Table 4), it is found that it takes 715 cycles to reach a water absorbency value of 0.5% as compared to 125 years of natural weathering so that 5-6 cycles of experimental weathering equates to one year of natural weathering.

An alternative approach was taken by comparing the properties of the new Killaloe slate with those of a used slate from the same quarry which is supposedly 200-year-old. This is a green slate with a gritty texture similar to the new sample. There are some visual signs of weathering such as slight brown staining on both surfaces, the exposed part of the upper surface is blackened and there are some rusty marks around the nail holes. Other changes due to weathering were investigated using XRD and XRF analyses (Walsh 1999).

It was found that water absorption had a value of 0.181%. Assuming that the sample had an initial water absorption similar to that of new slates from the same quarry, this corresponds to an increase of 0.081% or 0.00041%/year. This figure, when compared with the rate of increase of 0.00007% found experimentally in Fig. 3a, equates to 6 cycles of wetting-and-drying being equivalent to one year of natural weathering. However a better equivalence is again based on the exponential model of $\mathbf{y = 0.1038e^{0.0028x}}$. Using this equation it was found that it would take 561 years to reach a water absorption of 0.5%. which when compared with the 2385 cycles necessary to reach the same limit experimentally (Table 4) equates to 4 cycles of wetting-and-drying being equivalent to one year of natural weathering.

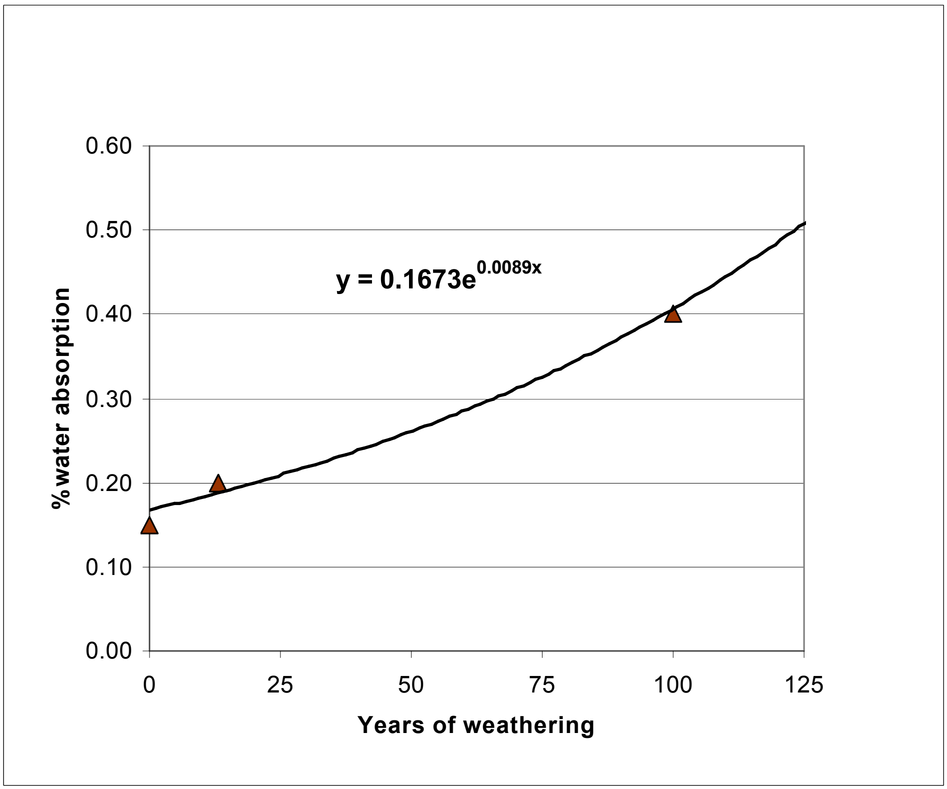

Fig. 5 Natural weathering of Ffestiniog slate

Given all the variations possible in the history of the different slates, let alone their imprecise ages (based on information from second-hand slate dealers), it is only possible to say that *4-8 experimental wetting-and-drying cycles are equivalent to one year of natural weathering*. Even the apparent agreement of the two estimates based on I/K-3 and W/F-8 above may be spurious and it is planned to carry our further comparisons between the effects of experimental and natural weathering in a Scottish climate.

Other changes is the properties of a slate due to weathering continue to be investigated, these include changes in the mineralogy and loss of strength. Other climatic environments will also be investigated such as exposure to acid vapour and biological weathering

6 CONCLUSIONS

Slates, experimentally weathered using wetting-and-drying cycles, show some of the characteristics of deterioration seen in naturally weathered slates. The increase in water absorption is one of the quantifiable effects which, when compared with that observed in a naturally weathered slate, gives an estimate of the number of cycles of wetting-and-drying equivalent to one year of natural weathering. Although the rate of deterioration increases with time, it is possible to use the **initial rate** at which deterioration takes place as a relative measure of the vulnerability of the slate to weathering. However a better estimate of the relative durability of different slates is based on an exponential model.

To minimise the effect on durability due to differences in the environmental conditions, rates of increase in water absorption were compared relative to that of a standard. The standard chosen was a Welsh slate to which was assigned a life expectancy of 100 years. All the other Welsh slates tested were found to have similar life expectancy values, the Cumbrian slates were slightly higher and the Spanish slates were approximately half that of the standard. These results agree with estimated values found in the trade literature (Walsh in press).

Being able to estimate the relative durability of different slates is the first step in determining the whole life costing of roofing material. A slate with a life span of approximately 50 years would have to be replaced several times within the useful life of one lasting 200 years. As a result, the less durable material would incur higher energy input overall from the extraction of the basic material at source to the transport and maintenance costs of the finished product when compared to its more durable counterpart. To date assessing the quality of different slates is reliant on the reputation of the slate in question. But reputation based as it is on past performance is not always the best guideline as there are many reasons why the quality of a slate from a particular source may change. This research attempts to set in place a protocol for assessing the quality of a slate objectively, enabling the identification of those slates that are easily weathered.

7 ACKNOWLEDGEMENTS

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