TEMPERATURE PROFILES OF DIFFERENT ROOF WATERPROOFING SYSTEMS SUBJECTED TO NATURAL EXPOSURE CONDITIONS

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The work of the British Board of Agrement involves the testing and the assessment of the likely service performance of innovative materials used by the construction industry. One of the most important attributes that has to be assessed is the service life of the product. As the materials the BBA work with are new, there usually is very little natural exposure data available and recourse has to be made to accelerated ageing tests. The problems of interpreting the data obtained from accelerated ageing tests are well known. There is the problem of whether the accelerator produces different effects from natural exposure; there is the problem of synergistic effects perhaps being missed. But the main problem is that we know very little about the actual environment in which building materials exist, which makes it very difficult either to design a sensible accelerated ageing test or to interpret the results of such tests.

One of the most important agencies in causing the deterioration of materials, in particular polymeric materials, is heating of materials by solar radiation. Not only does this in some cases cause true thermal ageing of the material due to thermal decomposition or by loss of volatiles, such as plasticisers, but it also affects the rate of decomposition because of chemical reactions such as oxidation or those due to ultraviolet radiation. In addition, the continuous changes in temperature, particularly where composite structures are involved, produce mechanical stresses in building materials which can cause failures.

Conventionally, the BBA together with other organizations has carried out heat ageing tests in a ventilated oven which is either at the maximum service temperature envisaged or at higher temperatures if it is known that these temperatures will create detrimental reactions, due to phase changes that would not occur in practice.

In the case of roof waterproofing materials this has usually involved heating materials at 80 degrees C for periods up to 156 days and periodically during this time measuring the changes in physical properties, such as tensile strength, elongation at break, cold flex temperature, softening point and fatigue resistance. Attempts to relate these results to changes in naturally exposed samples of materials are often frustrated by the long periods of time needed to obtain any significant changes in properties under natural exposure conditions and when recourse is made to natural exposure under more severe conditions, i.e. exposure in Arizona, there is again the problem of establishing the acceleration factor between the exposure site and the service conditions in which the material will operate.

The second problem area in predicting the service life of roof waterproofing systems has been in establishing the efficiency of protective systems applied to the roofing which can vary from thin paint type finishes through various thicknesses of gravel or chippings to the inverted roof system.

It was considered that the essential information that was required to sort out some of these problems was the actual temperature profiles that occurred under natural conditions, and for this reason, a number of roof systems have been subjected to continuous temperature measurements over the last two years.

The object of the program was to:

1. Examine the influence of slope and orientation to the sun of the roof samples on the temperature profile.
2. Examine the influence of various protective finishes on the temperature profile.
3. Record such meteorological data as might be useful to:
   a) allow prediction of a ten year-mean temperature profile; and
   b) possibly, allow prediction of temperature profiles or predict comparative ageing conditions on other sites where meteorological data has been recorded

The site used for the measurement was at the BBA's own site which is in the grounds of the Building Research Station which contains a meteorological site that has been in operation for approximately 40 years. The test site was within 150 yards of the meteorological site. Unfortunately the BRS site was closed down halfway through the program of measurements and some useful data, particularly on sunshine hours, rainfall and windspeeds has been lost. However measurements of the solar energy as well as the ambient air temperature were recorded continuously alongside the panels.

As a result of the relatively large number of samples to be used in the experiment, coupled with the need to take measurements as frequently as possible, it was necessary to carry out the measurements in two distinct phases. In the first phase from April 1, 1981 to March 31, 1982, the influence of slope and orientation on an exposed black waterproofing material was examined. In the second phase, which ran from January 1, 1983 until December 31, 1983, the effect of protection on horizontal waterproofing systems was examined.

SAMPLES

Phase I samples consisted of a 12mm plywood base with 50mm extruded polystyrene bonded to its upper surface with hot bitumen and a single layer of a black bitumen polymer waterproofing 1.5mm thick fully bonded to the upper surface of the polystyrene with hot bitumen. The edges of the bitumen polymer were folded around the edges of the panels and mechanically fixed to the underside of the plywood. Prior to fixing the waterproofing sheet a copper/constantan thermocouple was fed through a small hole drilled through the plywood and polystyrene so that its head was just proud of the upper surface of the polystyrene and made contact with the underside of the waterproofing sheet when it was applied.

Nine identical samples were prepared and fixed on a support approximately four meters from the ground. The panels were arranged to give the orientations shown in Table 1.

Phase II

All panels were one meter square and the thermal measurements were made in the center of the panel. The build up of the panels was as follows:

Sample 10: an inverted roof consisting of a 100mm dense concrete base to which was bonded the waterproofing with hot bitumen. 50mm of extruded polystyrene board was placed on top of this and weighted down with 150mm of gravel.

To the underside of the sample an insulated box was fixed containing an electrical heater and a control system. Thermocouples were placed on the underside of the concrete deck, on the underside of the waterproofing and on the top surface of the insulation.

Sample 11: was the same as sample 10 but the concrete base was replaced with a 3mm flat steel plate.

Sample 12: consisted of a 12mm plywood base to which 50mm of extruded polystyrene was bonded with hot bitumen followed by the waterproofing sheet. 150mm of gravel was applied to the top surface of the waterproofing.

A box containing a heater and control system was fixed to the underside of the panel and thermocouples attached to the undersides of the plywood, insulation and waterproofing.

Sample 13: as for 12 but no gravel protection.

Sample 14: as for 13 but no heater box attached. Thermocouples on underside of waterproofing.

Sample 15: as for 14 with the upper surface of the waterproofing painted with "silver" aluminum paint.

Sample 16: as for 14 with the upper surface of the waterproofing painted with a white reflective paint.

MEASUREMENTS

In Phase I, measurements of panel temperature were taken every six minutes. At the same time, the ambient temperature was recorded behind a Stevensons pattern screen immediately adjacent to the panels and the solar energy was recorded by means of two Kipp & Zoren CM.5 outdoor solarimeters, one placed horizontally and the other at 30 degrees to the horizontal facing south.

In Phase II measurements of panel temperatures, ambient temperature and solar energy were made at 20-minute intervals.

The data was fed through a logger onto paper tape and analyzed by computer.

RESULTS

It is impossible in a paper of this length to report fully on all measurements that have been made and some of the data is still in the process of being analyzed.

In Tables 2 and 3 the annual maximum and minimum temperatures recorded are given together with mean of all the daily maximum and minimum temperatures and the annual mean of all the temperature measurements made on a panel. In addition the maximum day, mean daily and annual temperature ranges are given together with the maximum temperatures recorded above and below ambient temperature.

In Tables 4 and 5 the annual temperature distribution in 5 degree increments is given as a percentage of time. The 80C equivalent period of time in hours relating to the years temperature distributions has been calculated by using the temperature coefficient for the velocity of reaction.

$$\frac{K_t + 10 = 2}{K_t}$$

In addition the thermal ageing index for the different panels has been given taking the unheated horizontal panel without any protection as the basis for the calculation in each case.

Table 6 gives the distribution of the maximum possible theoretical solar energy and the measured values for the two phases as a percentage of the available day light hours.

DISCUSSION

Phase I - The effect of orientation on the thermal profile. There is nothing very surprising in the values obtained. The north facing panels do not get as hot as the south facing but the low temperature conditions are practically identical for all panels. The comparative ageing index between the 30 degree south facing and the 30 degree north facing is approximately 1:0.6 which would give a significant increase in life expectancy for the roof covering without taking into account any benefit which may occur from the lower fatigue stresses that occur with the north facing panel. (See temperature ranges).

This ratio only will apply for sites around the same latitude as the test site and with similar sunshine hour conditions. In all other climatic conditions apart from bright sunlight* there was no significant difference between the temperatures of any of the panels. The time of bright sunlight on these panels was only approximately 15 percent of the total hours. For sites where the sunshine hours would be significantly higher than this, the difference in ageing index would be greater. The difference will become less at more southerly latitudes.

The results on these panels have confirmed that temperatures on the order of 80 degrees C can occur on black roofing under UK climatic conditions and it is therefore reasonable for a heat ageing test to be carried out at this temperature for unprotected roofing materials.

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* *The only other time that there was a significant difference in temperatures between the panels was during snow melting conditions when some panels were exposed and others still were covered. This explains the difference in the values for the maximum temperatures below ambient. The low temperature recorded on Panel 4 occurred on the night after the day the panel lost its snow. Panel 5 also lost its snow on the same day but the snow from Panel 4 slid down onto Panel 5 and effectively covered it.*

The measurements also have shown that the normally quoted maximum surface temperature of 40 degrees C above ambient for black materials can be exceeded by at least 10 degrees C.

Phase II - The Phase I panels were unheated on the underside and it was considered that, as insulation would usually be used only on heated buildings, the results obtained would not necessarily relate to practical conditions. In Phase II the opportunity was taken to examine the differences between unheated and internally heated panels of the same construction as the panels in Phase I. The underside of Panel 13 was maintained at a temperature of approximately 20 degrees whereas Panel 14 was unheated. The results show that this made no significant difference to the ageing index.

The protected roof systems show a number of different characteristics. With the inverted roofs the important heating comes from the internal heating, not from solar radiation. It was only after a hot dry spell lasting for several weeks that any significant temperature rise occurred with these panels. This is because in the UK climate liquid water is present on the surface of the waterproofing in the inverted roof situation for most of the year and this has to dry out before any significant heating can occur. In hot dry climates, periods of time at higher temperatures could occur. As a result of the large influence of the internal temperature the comparative ageing index, although less than for the exposed roof, is higher than initially envisaged, but the influence of thermal fatigue on inverted roofs is extremely low and occurs at temperatures which are above the normal brittle temperature of roofing sheets.

The results suggest that in the inverted roof condition, the waterproofing must have a high resistance to the effects of water, e.g. hydrolysis and to biological growth as the warm, moist conditions would be ideal for these to occur.

The 150mm gravel protection gives the best thermal protection. Not only is the comparative thermal ageing halved but the gravel prevents radiation loss to the night sky so that fatigue stresses at low temperature are reduced.

The white reflective paint is the better of the two thin coat protections giving the same protection from ageing as the 150mm gravel but no protection is given against radiation loss to the night sky and hence the possibility of fatigue damage is higher with these systems.

It is possible that the relative protection given by the various finishes will remain more or less the same for any site where the percentage of sunshine hours are similar to those experienced on the measuring site. In conditions of greater sunshine hours, the difference between the various systems will increase.

Panel 3 in Phase I and Panel 14 in Phase II are panels of identical construction where the thermal profile has been measured in different 12-month periods and, therefore, show the type of variation that will occur from year to year. The differences can be explained by the differences in ambient temperature coupled with the differences in solar energy distribution (Table 4) for the two years. It is hoped that further analysis of the figures will enable a relationship between solar energy and temperature rise to be established so that using available meteorological data for the site it will be possible to produce theoretical thermal profiles for other years and hence establish a mean ten-year profile for the site.

If this can be established then comparative predictions on other sites where climatic data has been collected may be possible, but the variables are numerous, including:

a) The ambient temperature profile—the temperature profile of a roofing sheet consists of the ambient temperature profile for the site modified by the influence of solar energy during the daylight hours and also by the loss of radiation to the night sky. The ambient temperature profile varies from site-to-site and can make a significant difference to the thermal aging of materials even when the influence of solar energy is similar. The ambient temperature profile generally can be obtained for any site where meteorological data has been collected.

b) The solar radiation intensity distribution—unfortunately, solar radiation has not been measured continuously on many meteorological sites. Where it has been measured, and if the relationship between the energy and temperature rise on the particular roofing system is known, then the ambient temperature profile can be modified to take account of the solar energy distribution. For the exposed black roofing sheet used in the measurements the mean energy* required to raise the temperature 1C was approximately $24 w/m^2$.

On sites where solar energy data is not available, it may be possible to calculate the approximate solar energy distribution by taking the theoretical maximum solar energy for the site, which can be calculated for any particular roof orientation and slope if the latitude of the site is known, and factoring this in relation to the mean sunshine hours experienced by that site. Sunshine hours are recorded on most meteorological sites.

c) Air movement across the roof. Movement of air across the roof will reduce the roof temperature and on particularly windy sites this could make a significant difference to the temperature profile. It is intended to examine the phenomena in more detail over the next few months. With the measurements that have already been made on the relationship between solar energy and temperature rise, there were a significant number of days when the measured energy required to raise the temperature 1C was approximately $14 w/m^2$. These can be assumed to be days when the influence of air movement was at its lowest.

The results suggest that on sheltered parts of the roof or in calm air conditions that temperatures of 70C above ambient would be possible for black roof materials.

d) Humidity, rain and snow conditions. The effect of moisture on the roof already has been mentioned in regard to the inverted roof system. Generally the effects of solar radiation are not noticeable unless the roof is dry. In the measurement, the horizontal panels reacted slower to early morning radiation than the sloping roofs due, presumably, to the inability of condensate or rain water to drain freely.

A covering of snow effectively insulates the roofing from

**This mean was calculated by taking the maximum temperature rise above ambient for each day and relating this to the solar energy intensity at that time. This mean is for the whole year excluding those days when the samples were covered with snow.*

solar energy, and in areas where snow cover remains for a considerable period of time, this would have to be taken into account in predicting temperature profiles.

CONCLUSION

There is still a long way to go before it will be possible to predict the thermal aging index for materials under different climatic conditions. Ideally, temperature measurements should be made on the same roof system on a number of sites in different climatic zones. The results from the various measurements have not yet been completely analyzed and this work will continue. The results already examined have given ideas on how our durability studies might be modified to suit certain situations and have given an index against which the BBA will be able to interpret its accelerated durability experiments with more confidence than before.

Panel No.	Facing Direction	Angle from Horizontal (°)
1	NORTH	30
2	NORTH	10
3	HORIZONTAL	0
4	SOUTH	10
5	SOUTH	30
6	EAST	30
7	EAST	10
8	WEST	10
9	WEST	30

Table 1

Panel No	1	2	3	4	5	6	7	8	9	Ambient
Facing	N	N	-	S	S	E	E	W	W	
Slope	30°	10°	0°	10°	30°	30°	10°	10°	30°	
Maximum temp. °C	57	70	72	77	78	71	73	72	70	32
Mean maximum daily temp. °C	26	32	34	38	40	33	34	34	34	15
Minimum temp. °C	-15	-16	-15	-16	-17	-16	-16	-15	-16	-13
Mean minimum daily temp. °C	3	2	2	2	3	3	3	3	3	6
Annual Mean temp. °C	10.7	11.6	11.7	12.3	12.4	11.4	11.6	11.8	11.8	9.3
Maximum day temp. range °C	51	64	67	72	72	62	67	66	63	20
Mean daily temp. range °C	23	30	32	35	37	30	32	32	31	9
Annual temp. range °C	72	86	87	93	95	87	89	87	86	45
Maximum temp. above ambient °C	35	45	45	50	51	45	46	44	47	-
Maximum temp. below ambient °C	-6	-7	-7	-12	-8	-8	-9	-9	-10	-

Table 2 Phase I - Annual maximum, minimum and mean temperatures

Panel No.	10	11	12	13	14	15	16	Ambient
Protection	Invert	Invert	150mm gravel	None	None	Aluminium paint	White paint	
Deck	Concrete	Metal	Plywood	Plywood	Plywood	Plywood	Plywood	
Int. temp °C	20	20	20	20	Amb	Amb	Amb	
Maximum temp. °C	31	37	37	70	70	60	46	33
Mean maximum daily temp. °C	20	23	15	33	33	26	19	15
Minimum temp. °C	16	15	-2	-14	-17	-15	-16	-7
Mean minimum daily temp. °C	19	19	9	3	2	3	2	6
Annual Mean temp. °C	19.9	21.0	12.0	13.8	13.3	12.2	9.6	10.5
Maximum day temp. range °C	6	13	16	64	64	52	38	20
Mean daily temp. range °C	1	4	7	30	31	23	17	8
Annual temp. range °C	15	22	39	84	87	75	62	40
Maximum temp. above ambient °C	-	-	9	42	41	29	14	-
Maximum temp. below ambient °C	-	-	-4	-8	-10	-9	-9	-

Table 3 *Phase II - Annual maximum, minimum and mean temperatures*

Panel No Temperature range °C		1	2	3	4	5	6	7	8	9	Ambient
>-10		0.3	0.4	0.4	0.4	0.3	0.3	0.4	0.3	0.3	0.2
-10	-5	1.7	3.2	3.1	2.9	2.4	2.1	2.8	2.6	2.3	0.7
- 5	0	10.0	12.9	12.6	12.3	11.3	11.2	12.4	12.2	11.5	7.2
0	5	18.3	17.6	17.8	17.5	17.6	18.0	17.8	17.7	17.8	18.0
5	10	24.4	20.7	21.1	20.7	13.7	22.2	21.1	21.1	21.6	27.6
10	15	18.4	17.6	17.7	17.7	18.5	19.6	18.2	18.1	18.8	25.1
15	20	10.0	8.7	8.6	8.4	8.7	9.4	8.7	8.7	8.9	14.7
20	25	5.0	4.8	4.7	4.8	4.9	5.0	4.8	5.0	5.1	5.1
25	30	3.9	3.5	3.6	3.7	3.7	3.7	3.6	3.7	4.0	1.4
30	35	3.4	3.1	3.0	2.9	2.9	2.6	2.9	3.1	2.9	<0.1
35	40	2.3	2.5	2.3	2.3	2.1	1.8	2.1	2.3	2.2	
40	45	1.4	1.9	2.0	1.9	1.8	1.5	1.9	1.9	1.6	
45	50	0.8	1.3	1.3	1.6	1.5	1.1	1.3	1.3	1.2	
50	55	0.2	0.8	1.0	1.0	1.3	0.7	0.9	0.9	0.8	
55	60	<0.1	0.6	0.6	0.7	0.8	0.5	0.5	0.6	0.6	
60	65		0.3	0.4	0.5	0.5	0.3	0.4	0.4	0.4	
65	70		0.1	0.1	0.4	0.4	0.1	0.1	0.1	0.1	
70	75				0.1	0.2		<0.1			
Equivalent hours at 80°C		108	140	146	169	176	131	144	145	142	-
Comparative ageing index		0.74	0.96	1.0	1.16	1.26	0.90	0.99	0.99	0.97	-

Table 4 *Phase I - Annual temperature distribution - percentage of time*

Panel No Temperature range °C		10	11	12	13	14	15	16	Ambient
> -10		-		-	0.2	0.8	0.3	0.5	-
-10	-5	-		-	2.7	3.3	2.9	3.4	0.4
-5	0	-		1.6	8.1	9.3	8.3	10.7	4.9
0	5	-		16.6	15.2	15.7	16.0	18.5	17.4
5	10	-		27.3	23.3	22.2	23.8	24.7	28.9
10	15	-	>0.1	23.0	19.2	18.4	19.4	19.9	25.4
15	20	64.9	48.5	16.0	9.1	8.6	10.2	9.7	14.5
20	25	31.8	41.8	9.4	5.1	5.0	5.3	5.0	5.9
25	30	3.2	7.9	4.4	3.9	3.7	4.0	3.3	2.3
30	35	0.1	1.8	1.6	3.1	3.1	2.9	2.4	0.3
35	40	-	0.1	0.2	2.5	2.5	2.5	1.3	
40	45	-		-	2.1	2.0	2.0	0.6	
45	50	-		-	2.0	1.9	1.3	<0.1	
50	55	-		-	1.5	1.5	0.6		
55	60	-		-	1.1	1.1	0.3		
60	65	-		-	0.6	0.6	-		
65	70	-		-	0.2	0.2	-		
Equivalent hours at 80°C		133	147	91	183	180	127	86	-
Comparative ageing index		0.74	0.82	0.51	1.02	1.0	0.71	0.48	-

Table 5 *Phase II - Annual temperature distribution - percentage of time*

Energy Range W/m^2	Theoretical Maximum	Phase I	Phase II
0 - 100	21.9	48.4	49.4
100 - 200	15.2	19.4	16.9
200 - 300	12.1	11.0	9.8
300 - 400	10.5	6.8	6.0
400 - 500	9.4	4.5	4.7
500 - 600	8.8	3.6	3.6
600 - 700	8.8	2.7	3.7
700 - 800	8.8	2.1	3.2
800 - 900	4.6	0.9	2.3
900+	-	0.6	1.0

Table 6 *Solar energy distribution as percentage of available daylight hours*