DURABILITY ASSESSMENT OF ROOFING MEMBRANES

JOHN C. BEECH
Building Research Establishment
Garston, Watford, United Kingdom

Monitoring the conditions of flat roofs in service, together with laboratory testing of membrane systems, has identified the flexural fatigue resistance as a primary performance index for the durability of bituminous membrane systems. Subsequent research into the performance of polymer modified bituminous materials and of single-ply membranes has shown that their fatigue resistance is extremely high; typically PVC and EPDM membrane specimens can withstand several millions of cycles of movement at 1mm amplitude, and fatigue resistance remains relatively high even after exposure to severe aging regimes in the laboratory.

Recent work has shown that measurements of the fatigue resistance of these high performance membranes, when performed at sub-zero temperatures, can reveal significant changes in the materials resulting from laboratory aging and from exposure to weather in severe climates.

This work is reviewed together with research on the fatigue endurance of built-up bituminous roof membrane systems, and the implications for the reliable prediction of the potential service life of membrane roofing systems are discussed.

KEYWORDS

Accelerated weathering, bituminous membranes, durability assessment, flexural fatigue, natural weathering, polymeric membranes.

INTRODUCTION

Since the 1960s, many flat and low-pitched roofs built in the United Kingdom and elsewhere have suffered from early failure and problems caused by leakage of rain through the waterproof membrane. The majority of these roofs were of the warm deck design,[1] in which a rigid foam plastics insulant, usually extruded polystyrene was sandwiched between the deck and a built-up bituminous felt membrane.

Surveys carried out by Building Research Establishment (BRE) and other organizations indicated that splitting of the membranes over joints in the insulant layer was a principal cause of failure. Measurements of the movement of roofs in service[2] demonstrated that built-up bituminous membranes incorporating organic fibre, asbestos and glass-fibre bases were particularly vulnerable to splitting when fully-bonded to extruded polystyrene insulation.

It has become apparent that adequate flexural fatigue is an essential requirement of roofing felts to enable them to withstand the thermal movements and other conditions of service. Suitable apparatus has been devised to evaluate fatigue resistance in the laboratory, using both small samples of roofing materials, and assemblies incorporating built-up membranes.

The range of materials investigated has been extended to include newer types of bituminous membranes with enhanced fatigue resistance and with greatly increased potential durability. These materials include felts incorporating bases of polyester fibres and oxidized bitumen coating, and others in which the properties of the bitumen are improved by the addition of suitable polymers. Polymeric materials of both thermoplastic and elastomeric types have also been subjected to cyclic flexural fatigue under controlled conditions.

The evaluation of durability has been based upon the exposure of membrane sheets and of built-up assemblies to weather in locations of different climatic conditions, and on the use of various artificial weathering and aging regimes in the laboratory.

Although other performance-related properties have been measured for laboratory and naturally weathered materials, and for controls, the flexural fatigue resistance has been identified as a primary index of durability in the work which is discussed in this paper.

FLEXURAL FATIGUE TEST APPARATUS

Two types of equipment have been developed by BRE for the evaluation of the flexural fatigue endurance of roofing membranes.[3]

The first was designed to test small samples cut from sheets of the materials, which were subjected to movements of 1mm amplitude over a gap width of 10mm, and with a frequency of 12 cycles/minute. The apparatus could be placed in a cold chest to operate at temperatures down to −20°C. Both bituminous and polymeric roofing materials have been tested using this equipment.

The second apparatus enabled 1200mm x 280mm assemblies incorporating built-up, multilayer weatherproof membranes to be subjected to cyclic movement at a simple butt joint in a suitable substrate such as plywood or foam plastics insulant.[3] The two substrate sections on either side of the butt joint were bolted directly onto two metal platens driven by electric motors through suitable gearing and cams allowing the amplitudes of movement to be varied. The apparatus is illustrated in Figure 1.

The movement of the first platen is intended to simulate diurnal movement in a roof joint; the duration of a complete sinusoidal cycle could be adjusted and was normally one minute. The second platen could be used to simulate seasonal cyclic movement so that the speed of movement was slower in the ratio of 1:365. For the work reported here, however, only the platen moving at the higher speed was operated, while the second platen was fixed securely to the supporting framework through two load cells, enabling the stress in the membrane to be monitored throughout testing, if desired. The large fatigue apparatus was housed in a room in which the temperature could be controlled in the range 0° to 25°C. Test assemblies incorporating membranes fully bonded with bitumen to a 25mm thick plywood substrate were tested using amplitudes of movement between 0.4mm and 3.0mm (the standardized amplitude used to test weathered and aged assemblies was 1.0mm).

ACCELERATED AND NATURAL WEATHERING

Two forms of accelerated laboratory conditioning have been mainly employed. The first involved exposure for various periods in ovens maintained at 80°C (with relative humidity controlled at about 78 percent when assemblies incorporating plywood bases were aged).

Simulated weathering, involving exposure to ultraviolet (UV) light and heat, and to water, was carried out in the QUV apparatus (Q-Panel Company, Cleveland, Ohio, USA). This comprises two banks of 40 watt fluorescent tubes giving radiant output in the wavelength range 280-320 um; UV(B) radiation in this range corresponds to the region of the solar spectrum received at the earth's surface which is most effective in causing degradation of polymers. Built-up assemblies and membrane samples were placed in the apparatus with their surfaces approximately 50mm from the lamps.

A reservoir of water within this equipment could be heated to generate water vapor, which condensed on the surface of the membrane as a result of heat loss from the back surface. The cycle of operation could be controlled to give alternate sequences of UV light and condensation. In this work a cycle of four hours UV followed by four hours condensation was used; during the UV sequence the temperature in the enclosure was 70°C.

Exposure of samples of roofing sheeting to weather was carried out at three locations; in the UK at BRE sites near London, in Dubai in the Middle East and at Freetown, Sierra Leone, West Africa. Normally 300mm x 300mm samples were cut from sheets of commercial products and fixed on south facing racks at 45° inclination. The 1200mm x 280mm assemblies of built-up bituminous felts were exposed only in the UK, where they were inclined, facing south, at approximately 5° to allow rain to drain from the surfaces.

TESTS ON BITUMINOUS MEMBRANES

The relative fatigue endurance of the different bitumen-based roofing materials is indicated in Table 1 which gives the number of cycles to failure for unaged 152mm x 12.5mm samples, and after heat aging for 28 days at 80°C.

Only membranes comprising glass-fibre based and polyester-based (oxidized bitumen) felts together with a few products having a base of glass fibre with polyester, have so far been tested in the form of built-up assemblies. The specifications tested in this form are summarized in Table 2.

Detailed data relating to the effects of temperature and amplitude of movement on the fatigue endurance of Type I assemblies were obtained.[3] These will not be considered here. As a basis for comparison of relative durability, the fatigue resistance measured using standardized amplitude of 1mm will be discussed. The majority of data were obtained at 25°C, and these provide the basis for comparing the relative fatigue resistance for the different built-up specifications described in Table 2. These were of the following order for unaged assemblies:

- Type I—Three layer glass-fibre base ◀600 cycles.
- Type IV—Two layer glass fibre/polyester 600 cycles.
- Type III—Three layer glass fibre/polyester 4,500 cycles.
- Type II—Two layer polyester based ▶30,000 cycles.

Clearly the enhanced fatigue resistance measured on small samples of the polyester-based felts, as compared with conventional glass-fibre felt is fully realized in the data obtained from built-up assemblies. In testing built-up assemblies, the approach is more closely related to the construction of the bituminous membranes used on flat roofs, thus the test is more "realistic" than one carried out on a single-sheet sample. However, this realistic fatigue test introduces additional factors, which also reflect the reality of the true service environment, but make unambiguous assessment of the test data considerably more difficult.

In closely observing the progress of a fatigue test on a multilayer, built-up assembly, it is observed that failure may proceed by a succession of delaminations between the substrate and the first felt layer, and between contiguous felt layers; and of cracking of the individual felt layers in close proximity to the butt joint in the substrate. Failure may be judged to have occurred when a crack becomes clearly visible in the exposed top layer of felt, through which water can penetrate.

Because the occurrence of delamination effectively reduced the local stresses in the felt layers close to the butt joint, it had the effect of delaying the fatigue failure of the individual felt layers, and hence of the whole assembly. This introduces considerable variability into the test data, since when delamination occurs over an area adjacent to the butt joint, failure may occur (if at all) only after 15,000 or more cycles of movement.

A further uncertainty was introduced into the results of tests on polyester-based felt assemblies, since cracking was often deemed only superficial, and did not appear to penetrate to the base of the felt. This made the judgement of failure problematic.

In the discussion of the results obtained from laboratory and naturally weathered assemblies, these effects should be borne in mind. These fatigue data were obtained from tests on assemblies of two of the types of built-up membrane listed in Table 2: Three layers of conventional glass-fibre based felt (Type I); and two layers of polyester-based felts (Type II B). Fatigue tests were carried out to failure (or to 15,000 cycles) at temperatures of 2°, 10°, 18° and 25°C after different durations of natural weathering or exposure in the laboratory. The average values of cycles to failure (or of the first sign of surface cracking) are given in Table 3. Generally three assemblies were tested in each case, though data in Table 3 are based on fewer results if one or more assemblies survived more than 15,000 cycles.

The data in Table 3 exemplify the difficulties inherent in using fatigue data for built-up bituminous felts to compare the performance of different specifications, and to attempt a correlation between fatigue endurance after exposure to weather and to laboratory weathering regimes. Despite the cracking observed on the surface layers of the polyester-based assemblies, it proved impossible to produce a true failure of these membranes (comparable with that of the glass-fibre assemblies), even after the most severe laboratory aging and with onerous fatigue testing at 2°C.

In the latter stages of this work, polyester-based assemblies, which had been exposed to 56 days of heat aging at 80 °C followed by 56 days in the QUV apparatus, survived over 15,000 cycles of 1mm amplitude movement, showing merely fine superficial cracking.

Although the previously mentioned delamination effect accounts in large measure for these observations (and for the anomalous data for glass-fibre membranes after exposure to natural weather), it must be concluded that polyester-based membranes show marked resistance to fatigue which is likely to contribute to good durability in service. Examination of a large number of flat roofs covered with this type of built-up membrane after a minimum of 10 years in service, in the UK, has in fact revealed no failures due to deficiencies in the felt layers; in the few cases of water penetration identified, the cause was attributed to poor detailing of the roofs.[5]

It is clear that fatigue testing has serious limitations for the assessment of high performance bituminous membranes, and for the evaluation of laboratory aging procedures as a means of predicting the durability of these membranes. Other approaches which are under investigation include the use of cold bending tests on small single-membrane samples, which may be suitable for the detection of changes in the material affecting the long-term performance of the membranes in which these products are incorporated.

Other possibilities for developing the evaluation of the durability of roofing membranes, equally applicable to bituminous or to polymeric systems, will be discussed in the final section of the paper.

TESTS ON POLYMERIC MEMBRANES

Fatigue tests have been carried out on small samples of polymeric, single-ply roofing membranes. The material included the following:

- PVC I—Reinforced, thermoplastic polyvinyl chloride.
- PVC II—Non-reinforced PVC.
- PIB—Polyisobutylene, thermoplastic non-vulcanized sheet, with fleece backing.
- CSM—Chlorosulphonated polyethylene, thermoplastic rubber sheet.
- EPDM—Two products based on vulcanized elastomeric sheeting of ethylene propylene diene terpolymer rubber.

Early tests of fatigue endurance at 25 °C using PVC and EPDM roofing products establish their high resistance; neither showed any sign of failure after some millions of cycles of movement at 1mm amplitude. Later tests on the whole range of products listed, showed that all were capable of withstanding at least 3 x 10^6 cycles of this amplitude at 2 °C.

Subsequent tests on these materials including samples from material exposed to weather and after laboratory aging were all carried out at − 20 °C, maintaining the standard 1mm amplitude of movement used in earlier work. Sample size was 50mm x 50mm and the distance between the grips of the fatigue machine was 10mm.

The results of these tests are summarized in Table 4. Tensile tests were also carried out at 25 °C on samples of the non-reinforced membrane materials, before and after the weathering and aging procedures. In none of these materials was there any significant change in tensile properties, such as modulus or extensibility, as a result of these exposures.

It is apparent from Table 4 that at a temperature of − 20 °C, the fatigue test reveals marked differences in the behavior of the different materials, and in their response to exposure to degradation factors such as heat and UV radiation. These differences are illustrated in Figure 2.

The two EPDM products showed virtually no change in any of the exposures; the PIB membrane while unchanged by the laboratory aging, and by exposure to the moderate UK climate showed some reduction of fatigue resistance in the more severe climates, with Dubai proving more damaging than Sierra Leone. The Dubai climate was extremely onerous for the CSM membrane while Sierra Leone and UK exposures caused progressively less, though still significant, reductions in low temperature fatigue endurance for this material.

In contrast, the two PVC membranes were most affected by the climate in Sierra Leone, which rather closely reflected their performance with the QUV laboratory exposure.

In general then, some qualitative correlation may be noted between the changes in fatigue resistance at − 20 °C for weathered and laboratory-aged, polymeric roofing membranes. Closer examination of the data relating to just over four years exposure in the climates with high UV intensity, and for the QUV exposure, reveals a fair degree of quantitative correlation. Figure 3 shows the relevant data plotted on logarithmic co-ordinates, from which it is seen that the fatigue resistance data for Sierra Leone samples correlate strongly with those for the QUV samples (significant at the 0.1 percent level).

The reason for the good correlation appears to be that while EPDM and PIB are relatively unaffected by both environments, the hot humid conditions of Sierra Leone, with high intensity of UV radiation, produce changes in PVC membranes of similar large magnitude to those induced by QUV exposure. The QUV weathering equipment appears to be capable of simulating in these materials the degradation caused by exposure to climates with high intensities of UV radiation. The equipment seems, therefore, to have potential for discriminating roof membrane materials which are likely to prove durable in these climates. This needs to be confirmed by using a wider range of materials, and by measuring also other performance-related properties after exposure of samples to natural and artificial weathering.

ASSESSMENT OF DURABILITY

The flexural fatigue resistance measured on small samples of membrane materials has been proposed[6] as an effective index for characterizing the wide range of roofing membranes on the market in terms of the potential durability of the materials comprising the waterproof covering. Although certain minimum values of both tensile strength and elongation to failure are necessary to ensure the integrity of the coverings, neither is related as closely as fatigue resistance to the primary requirement of combating the effect of thermal and moisture movements in service. The connection between fatigue resistance and service life has been demonstrated by the performance of those bituminous membranes for which BRE has some years of experience in service.[3,5]

The major categories of membrane products are listed in Table 5, with an indication of their fatigue endurance before and after heat aging.

The improvements in fatigue resistance between the categories listed are in order of magnitude, and it has been shown that in the case of multilayer bituminous systems, it can be reasonably expected that this enhancement will be fully reflected in the performance of the built-up roof coverings. For the assessment of the durability of all these categories of roof coverings, it is evidently necessary that performance criteria should be developed which relate to "fitness for purpose" of the complete roofing system, and to the maintenance of certain key properties which relate directly to the satisfactory performance of its functions.

While flexural fatigue resistance appears to be such an essential performance index, there are practical difficulties associated with its measurement in the laboratory for durability assessment, which have been identified in this paper.

In the case of single-ply polymeric membrane systems, the fatigue resistance of the materials themselves is unlikely to be a limiting factor upon their successful use in forming durable weatherproof coverings on flat and low-pitched roofs. In the case of mechanically-fixed membranes, the stressing of the membranes caused by rapid fluctuation of pressure over the roof surface will usually be more relevant than stresses associated with thermal movement in the roof. Performance assessment of this type of single-ply membrane must be carried out using special equipment designed to simulate these stress factors in the laboratory.[7] For both mechanically-fixed and bonded-types of polymeric membranes, the ease with which satisfactory joints between sheets can be formed on the roof during laying, and the durability of these seams in service is likely to most strongly influence their effective service life.

Work is in progress to investigate suitable means of laboratory testing of the joints between sheets of single-ply roofing. These include both cyclic stressing of test joints and long-term loading based upon the measured tensile strength of joints, to evaluate creep properties.

The data presented for laboratory weathering of single-ply materials using the QUV apparatus suggest that further research may be fruitful to investigate the relationship between different laboratory exposures, in which the balance between UV, heat and water as degrading factors is varied, and the effects of widely different climatic exposures on key membrane properties. However, it should be recognized that there are formidable problems associated with establishing reliable correlation between natural and accelerated laboratory weathering for the wide range of polymeric and bitumen-based materials with which there is concern. In previous research where correlations have been satisfactorily demonstrated, these have usually been limited to one type of material and to one specific climate. The outcome of the work by Marechal,[8] which established a relationship between various properties of polymer-modified bituminous sheetings after heat aging and after exposure to a southern European climate, is typical of these correlations.

Dupuis[9] has reported another approach to durability assessment for which the tensile properties of field samples taken from polyester-reinforced, built-up membranes were measured. An attempt was also made to assess the water-tightness of these membrane samples while under various degrees of extension, in relation to their measured elongations at failure. The longest period of exposure to weather was for five years in Texas. This study offers another potential means of evaluating the durability of flat roof coverings, particularly if suitable samples can be obtained for testing from membranes which have shown failure after a known period of service.

Finally, there must be mention of the possibility of employing sophisticated thermal mechanical techniques for the analysis of changes in membrane materials resulting from exposure to weather or to laboratory accelerated weathering and aging regimes.[10] These techniques, which include dynamic mechanical analysis (DMA), thermo-gravimetric analysis (TMA) and torsion pendulum measurements, offer a sensitive means of identifying changes in the glass transition characteristics of membranes, induced by these various degradation factors in weather which are primarily responsible for changes in performance related properties such as the fatigue resistance which have been discussed in this paper.

A collaborative international program of research is in progress under the auspices of RILEM Technical Committee 120-MRS (formerly 75-SLR) and CIB Working Commission W.83[11] in which BRE is participating. An important objective of this program will be to relate the results of thermal mechanical analysis to those membrane properties which have been conventionally measured in the laboratory, and to the changes in these caused by degradation during exposure to weather, natural and artificial.

REFERENCES

[1] BRE Digest 221, Flat roof design: the technical options, Building Research Establishment, 1980.

[2] Beech, J.C. and Saunders, G.K., "The movement of foam plastics insulants in flat roofs," *Building and Environment,* 19, No. 2, 65-74, 1984.

[3] Beech, J.C. and Hudson, R.W., Joint movements in foam plastics flat roof insulation, Paper presented at 2nd International Symposium on Roofs and Roofing, Brighton, England, 1981.

[4] Specification for roofing felts, BS 747:1977 (incorporating Amendments 1, 2 and 3), British Standards Institution.

[5] Survey by Building Research Establishment for British Flat Roof Council, 1987.

[6] Beech, J.C. and Dinwoodie, J.M.W., "Preventing water penetration in flat and low-pitched roofs," *Building Technology and Management,* 20, (10), 21-27, 1982.

[7] Redfearn, D., A test rig for proof-testing building components against wind loads, BRE Information Paper IP 19/84, Building Research Establishment, 1984.

[8] Marechal, J.C., Comporteiment mechanique des revetements d'etancheite, Viellissement des bitumes elastomeres et des bitumes oxydes, cahier de CSTB, no-2105 Centre Scientific et Technique du Batiment 1986.

[9] Dupuis, R.M., "Strain energy and elongation behaviour of field samples taken from polyester reinforced built-up roofs," *Roofing Research and Standards Development,* Second Volume, ASTM STP.1080, Thomas J. Wallace and Walter J. Rossiter, Eds. American Society for Testing and Materials, Philadelphia, 1990.

[10] Farlling, Michael S., "New laboratory procedures to evaluate the durability of roofing membranes," *International Journal of Roofing Technology,* Vol. 1, No. 1, 71-76, National Roofing Contractors Association, 1989.

[11] "Performance testing of roofing membrane materials," Recommendations of RILEM 75-SLR/CIB W.83 Joint Committee on Elastomeric, Thermoplastic and Modified Bitumen Roofing, November 1988.

[12] Beech, J.C., "Performance assessment of flat roof membranes," *International Journal of Roofing Technology*, Vol. 2, 13-19, National Roofing Contractors Association, 1990.

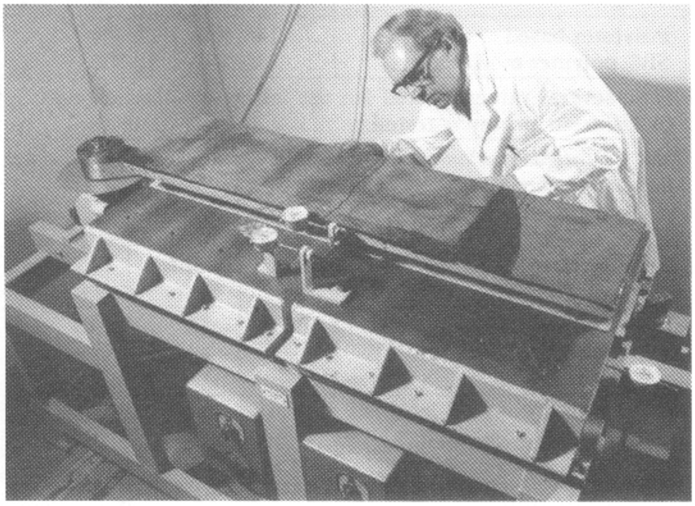

Figure 1 *Fatigue test machine.*

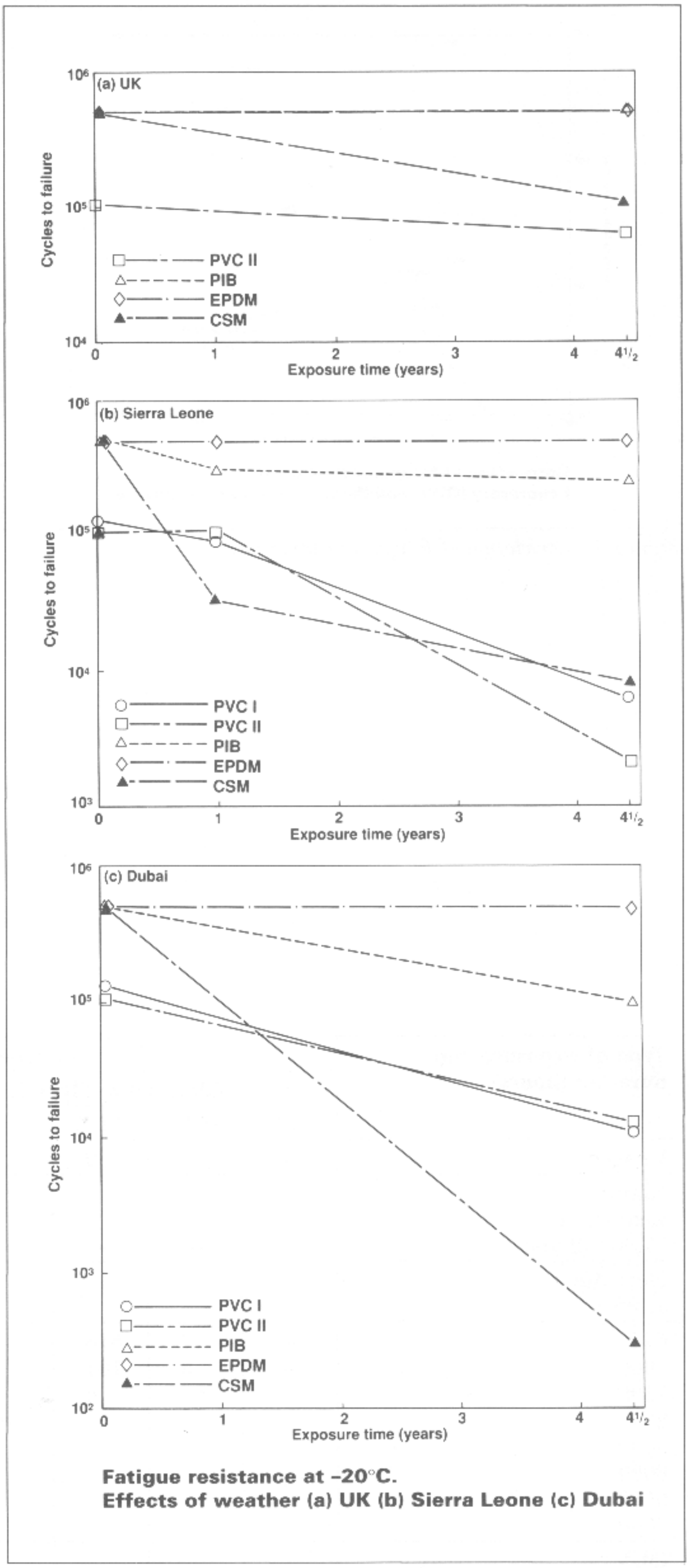

Figure 2 *Fatigue resistance at −20°C.*

Sample Code (Type)	At +2°C		At −20°C					
	Unaged Material	Unaged Material	Laboratory Aged Samples		Field Exposure			
			Heat Aged at 80°C	QUV at 70°C	UK 4+ yr	Sierra Leone 1 yr	Sierra Leone 4+ yr	Dubai 4+ yr
PVC I	3 x 106s	129,841	135,819	18,628	—	91,862	6,108	11,327
PVC II	3 x 106s	106,688	62,541	9,508	62,812	110,749	2,081	13,474
PIB	3 x 106s	500,000 s	500,000 s	500,000 s	500,000 s	335,072	248,858	100,796
EPDM	3 x 106s	500,000 s	500,000 s	500,000 s	500,000 s	500,000 s	500,000 s	500,000 s
CSM	3 x 106s	500,000 s	—	—	107,448	34,517	7,921	294
S: No failure reported, · No data yet available								

Table 4 Polymeric membranes: Number of cycles to failure.

Category	Type of roof coverings	Layers in system	Average flexural fatigue resistance (cycles) at 25°C	
			Unaged	Aged for 28 days at 80°C
1	Reinforced bituminous felts to asbestos-based BS 747[4]	3	150	30
	glass-fibre based	3	150	80
2	Reinforced bituminous felt (BS 747 Amendment No 3 1985), polyester-based	2	6,200	3,200
3	Reinforced polymer-modified bituminous felt, polyester-based	2	►140,000	21,000
4	*Bitumen or pitch polymer membrane	2	150,000	70,000
5	Flexible single) PVC, layer sheeting) Butyl, EPDM	1	►10^6	►500,000
*Bitumen is referred to as asphalt in North America.				

Table 5 Categories of roof covering and their fatigue resistance.