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GLASSMAT AS A BASE FOR BITUMINOUS ROOFING MEMBRANES

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This paper deals first with the historical development of roofing membranes, with emphasis on the base material, and then with research, carried out on bituminous roofing membranes during the last 10 years.

I. HISTORICAL DEVELOPMENT.

Until about 20 years ago, ragfelt, as the most widely known, and asbestos felt, were the most important base-materials for roofing membranes. Raw materials for ragfelt comprised a large variety of organic fibres: wool and cotton-rags, cellulose-fibres, paperfibres, etc. They are sensitive to moisture, resulting in a decrease in strength, a risk of rotting and pimpling of the roofing membrane.

Pimpling is caused by expansion of moisture still present or accumulated in open spots in the felt or in hollow fibres. To minimize these risks the fibre felts have to be saturated with bitumen of low viscosity at the production temperature.

Another well known problem with bituminous ragfelts, when applied fully bonded to the substructure, is blistering. The causes are moisture entrapment in an apparently dry substructure, or even air entrapment. The vapour bubble underneath the roofing membrane can expand itself by daily heating/cooling cycles, and the vapour can move to the bubble at moments of underpressure.

Some 20 years ago, the first glassfibre mats were introduced. Promising features were the inert, moisture resistant character of glass, and its high strength. These first glassmats were produced through a so called dry process. Glassfibres, produced from a melt, or pulled from glassrods, were distributed on a conveyer belt, followed by a binding step, in which a thermosetting organic binder was generally used. Glassmats have a much more open structure than ragfelt and are therefore easy to impregnate. The first glassmats were not very strong, compared with dry ragfelts; tensile strength of the glassmats were about 10 kgf/5cm longitudinally and about 6 kgf/5cm transversely. Yet they have generally been used quite satisfactorily, due to the rather heavy and rigid building constructions at that time, combined with the then-developed laying methods, allowing for some movement in the substructure.

Some 15 years ago, van Gelder and Sons, a Dutch paper manufacturer, developed the idea of producing fiberfelts with a wet process, derived from paper production technology. In this process a dispersion of fine fibres in water is used. The dispersion is transfered to a conveyer-belt, dried, and the fibres are bonded together by the polymerisation of an organic binder, already present in the dispersion, or applied by spraying on the fibre mat.

As its chief advantage, this process produces regular mas, without orientation of the fibres in the machine-direction.

The process was worked out in cooperation with our roofing company, first with synthetic fibres. We chose nylon fibres for the production of felt with high strength and high elongation. The reason for this choice was our belief that an increasing number of failures comprised the breaking of the membrane across joints in the substructure. We concluded that improvements of roofing membranes should consist of increased tensile strength and elongation. A nylon fibre felt was produced of ca. 40 gr/sq.m., with a tensile strength of ca. 23 kgf/5cm in machine direction and an elongation till break of ca. 16%.

After a production of roofing membranes with this base some tests were carried out with a sheet fully bonded to a wooden structure, in comparison with bituminous glassmat and ragfelt. After a period of about a month it appeared in the case of nylon felt that above the joints a ridge had formed, with signs of cracking of the bitumen coating. The base itself was still in good shape.

Our conclusion was that the base of a bituminous roofing sheet, when subject to the repeated movements of the substructure, in the first place should have a high tensile strength at a limited elongation of about 2%. From then on, the collaboration between van Gelder and CKK was directed to the development of glassmats from a wet process. Our aim was a glassmat with a tensile strength of 25 kg/5cm in both directions, at an elongation of ca. 2%. This strength was about 50% higher than the strength of glassmats used at that time, which were in general much weaker in cross direction than in machine direction. Although the first production trials were very promising, we had to overcome several problems: finding the right fibre size, improving the homogeneity of the mat, and finding the best binder and binding percentage.

The results were a glassmat of high quality, which has been used now for about 10 years. Some properties of the wet process N.25-glassmat are given in Table I, in comparison with a 50 gr. glassmat, used 10 years ago.

TABLE 1

	VAN GELDER - N.25	COMPARISON
Tensile strength MD (Kgf/5cm)	>25	ca. 15
CD	>25	ca. 10
Elongation	2-2.5%	1.5-2%
Regularity - (weight distribution): ±15%	97%	81%
±20%	-	95%
Wet strength (In % of dry strength)	80%	ca. 30%
Weight per sq.m.	ca. 50 gr/sq.m.	ca. 50 gr/sq.m.
Fibre thickness	10±0.5/um	80% : 10-14 /um

The regularity can be expressed as the percentage of individual weight-measurements (50 cm^2-samples) falling within certain tolerances on the mean sq.m.-weight.

Dry-process glassmats have also been improved considerably since 1965, but to attain comparable tensile strength, they must be heavier and thicker (>70gr/sq.m.).

Development of the glassmat for our roofing sheet Vitrix N.25 has inspired more fundamental research into the mechanical properties of roofing membranes, and to the functions of the component parts of a roofing membrane. Some of this work will be discussed in the second part of this paper.

II. MECHANICAL PROPERTIES OF BITUMINOUS ROOFING MEMBRANES.

II.A. Influence of the components on the strength of the membrane.

- What effect do the two components, bitumen and felts, have on the mechanical properties of the finished product under different conditions of temperature and loading time?

This was investigated on three base-materials and their finished products: ragfelt, nylon-fibre felt and glassmats.

On these 6 materials, we measured the tensile strength and %-elongation until break at different speeds of tensile testing. From the stress and strain values, the Elastic Modulus was calculated as E = load per sq.m., divided by the specific elongation.

$$E_{prod.} \times S_{prod.} = E_{base} \times S_{base} + E_{coating} \times S_{coating}.$$

where S = surface area of crossection; $S_{prod.} = S_{base} + S_{coating}$.

The Elastic Modulus of the bitumen (stiffness) at the time of loading and temp. was dervived from the Shell-nomogram of Van der Poel.

There was good agreement between the calculated E-modulus of the products and the measured values. Therefore we may conclude that the formula, as used for example for reinforced concrete, also applies to bituminous roofing sheets. Moreover, it appears that at loading times of 10^4-10^5 second, being about the daily cycle, the mechanical properties of the bituminous ragfelts and glassmats are mainly determined by the base, even at low temperatures (high stiffness). For bituminous nylon-fibre felt however, the bitumen does play a considerable part at these conditions. Because of the felts' dominant role in determing mechanical properties, improvement of bituminous fibre felts can best be done by improving the base. .

II.B. Fatigue-behaviour.

Changes in roofing constructions made improvment of the roofing membranes more and more necessary. Use of thermal insulation increased, and the constructions became lighter and less rigid. The roofing membrane must accomodate the consequently larger movements of the substructure. Most damage occurs after some time by break of the membrane above a joint or split in the substructure.

The behaviour of roofing membranes, fully bonded to the substructure across a moving joint, became of great interest. When does a crack in the roofing sheet occur above a constantly widening gap, or above a repeatedly moving gap?

This matter has been studied in several different ways. First, we carried out a series of experiments on strips of bituminous roofing materials fully bonded across a slit between two metal plates. One of the metal plates was fixed, and to the other one a constant load could be applied until the membrane ruptured. These experiments were carried out, with different materials, at different temperatures and different constant loads.

Another series of experiments was carried out with a constant gap-widening speed, instead of applying a constant load. The force developed was recorded and the gap at membrane rupture measured.

The results of this work have been laid down in the formula:

$$g = 2\sigma_0\sqrt{\frac{3h}{E\times S}}$$

g = gap width at rupture (mm)

where

σ_0 = force (N/m) necessary for moving the substructure
h = height of the bonding bitumen layer
E = Young's modulus of the base
S = stiffness of the bitumen.

From this relationship it can be seen that the maximum gap that can be bridged in a single movement is proportional to the tensile strength of the base. Rupture occurs when σ_0 is equal to the tensile strength of the base.

When two base materials have equal tensile strength, then the base with the smaller E-modulus (and thus a higher elongation until break) will have a greater gap-bridging capacity. Moreover, the lower the stiffness of the bitumen, the greater the gap that can be bridged in a single movement.

Some results are given below in Tables II and III, from which the effect of the base and bonding bitumen can be seen.

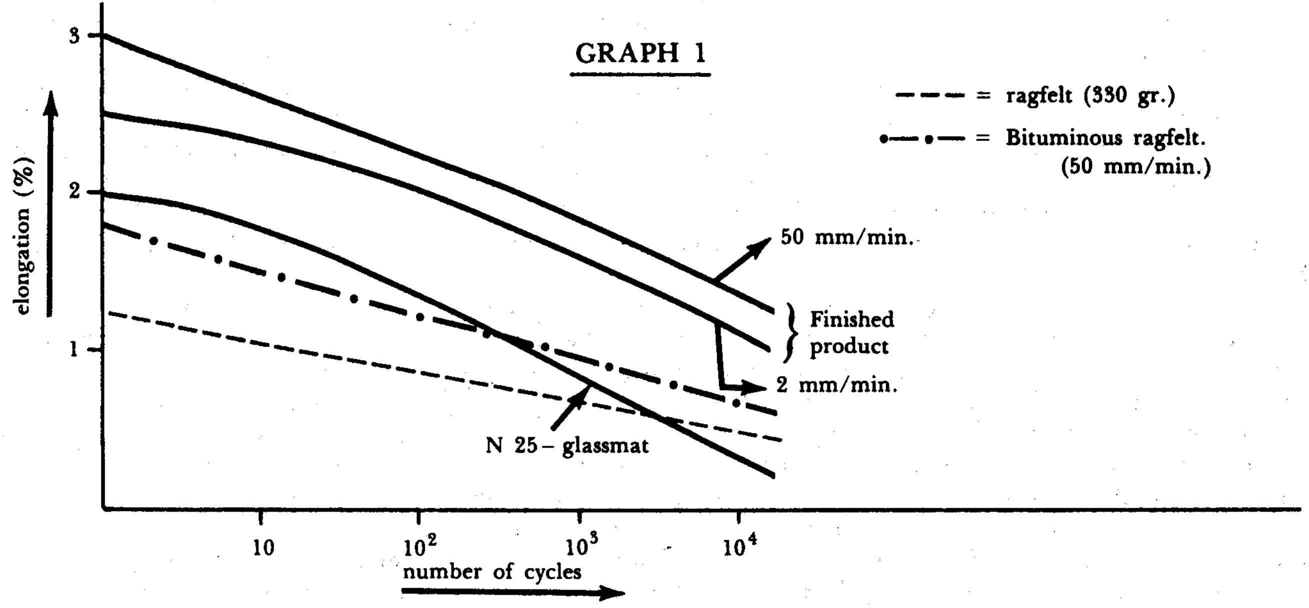
II. EFFECT OF THE BASE	BASE	GAPWIDTH (mm)
Circumstances:	glassmat N25 25kgf/2.5%	3.4
h = 1.5 mm	ragfelt 330	2.3
T = 20°C	ragfelt 500	3.0
Bitumen 110/30	glassmat 10kgf/2.0%	2.0
V = 0.2 mm/hr.		

III. EFFECT OF THE BITUMEN	BASE + BITUMEN	GAPWIDTH (mm)
Circumstances:	glass 25kgf/2.5% + 110/30	0.95
h = 1.5 mm	glass 10kgf/2.0% + 110/30	0.48
T = -10°C	glass 10kgf/2.0% + 85/40	0.52
V = 0.2 mm/hr.	glass 10kgf/2.0% + 85/25	0.25

In these first experiments, we measured the development of stress in the base as a consequence of a single movement of the substructure.

What happens if a certain movement is carried out repeatedly? Fatigue endurance has been studied extensively during the last 10 years. From the experimental work a mathematical model has been worked out. At the Brighton Roofing Symposium in 1974 a paper was presented about this work by Dr. Bonafont.

The first fatigue-experiments involved the testing of strips of roofing material in a tensile tester, repeatedly loaded between fixed percentages of elongation. This has been done with the glassmat N.25 and its finished product. The experiments were done at different speeds. Results are given in Graph 1.

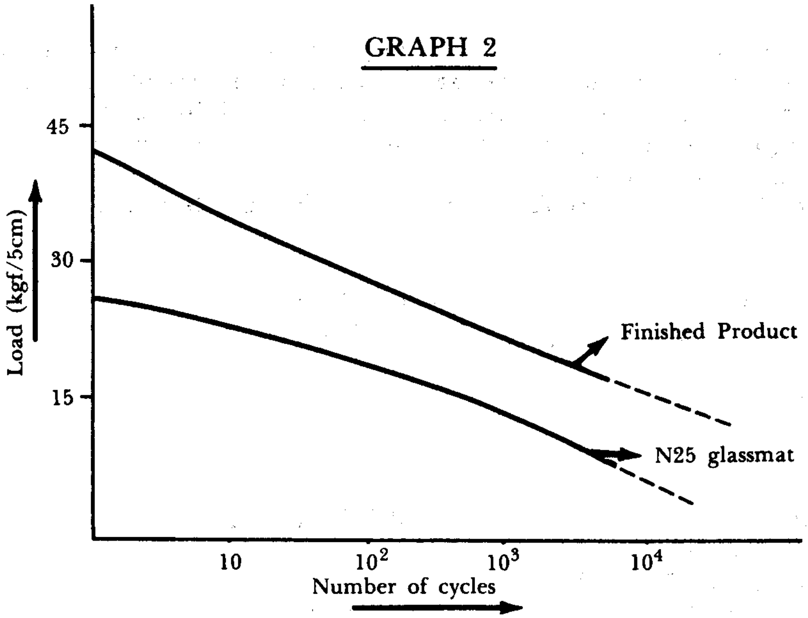


GRAPH 1

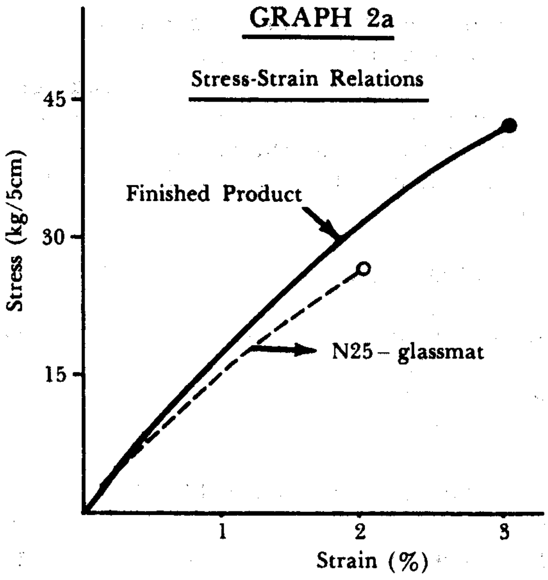
For the glassmat the deformation rate exerts no apparent influence on the number of load-cycles at a certain percentage of elongation. For the finished product however, the deformation rate does have an effect on fatigue properties. At lower rates fatigue resistance is lower for the bituminous product.

These kinds of experiments were repeated, but then instead of loading between certain percentages of elongation, the cycling was carried out between fixed values of stress. These experiments were only done at a deformation rate of 5 cm/min. Results are given in Graph 2.

The question was then: "Is there an agreement between these two kinds of experiments, cycling between values of elongation and between stress-values?" These two kinds of experiments can be compared by using the stress-strain relation for the base material, and for the finished product, taken from a normal tensile testing of the materials. This relation for glassmat N.25 and its product is given in Graph 2a.



GRAPH 2



GRAPH 2a

Stress-Strain Relations

For example:

Cycling between 0 and 1 % elongation corresponds to cycling between 0 and 15 kgf/5cm for the glassmat. In the first case, the experimental number of cycles is 500, in the second case the number of cycles found is also 500.

Thus we might conclude that in case of cycling the glassmat itself, there is a good agreement between the two kinds of cycling experiments.

In the case of the bituminous glassmat, there is no apparent agreement. The number of cycles that can be carried out between certain stress-limits is smaller than for the corresponding cycling between elongation values.

This could, however, be explained from the way the experiments are carried out. Suppose a strip of the bituminous product is cycled between 0 and 1% elongation. After a number of cycles, the corresponding stress at 1% elongation is decreased. In case of cycling between certain stress-limits, the deformation has then to be increased, to maintain the same stress value at the end of a cycle. Such an increase in deformation will result in a decrease in the number of cycles that can be applied. This decrease in stress after some cycles at a fixed % of elongation may be due to a certain slip from the clamps, but it is also easy to understand that an imperfectly elastic material (and the finished product will certainly not be purely elastic) will undergo a certain lasting deformation, after some loading cycles, and this deformation will increase after each cycle.

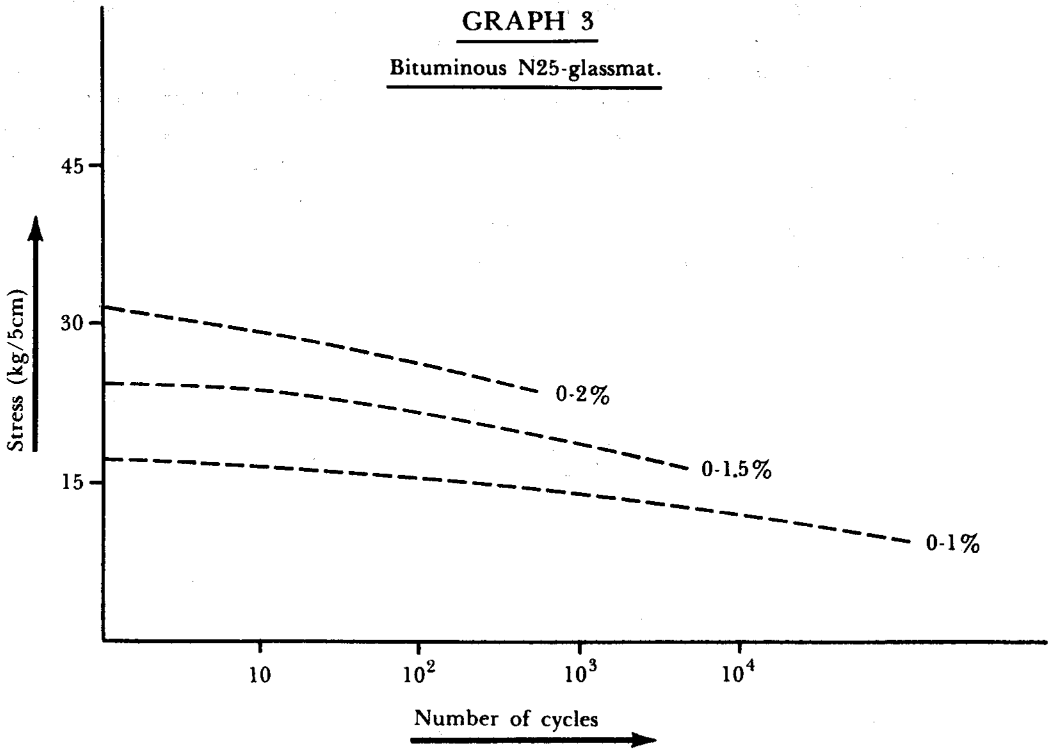
This decrease in stress when cycling the finished product with glassmat as a base between fixed % of elongation is shown in Graph 3.

Cycling-experiments between fixed elongation-values were also carried out on a weaker glassmat (13.5 kgf/5cm) and on ragfelt 330 and their finished products. Their results are also given in Graph 1. These experiments were not repeated with cycling between stress values. On ragfelt this would not have given meaningful results.

Unlike glassmat, ragfelt is a non-linear-material. When a strip of ragfelt is loaded, the deformation is not purely elastic, but much more a permanent deformation, due to fibreslip. Cycling between stress-limits would have soon resulted in break of the material, in contrast with cycling between elongation limits. Further fatigue-endurance research has been carried out since 1970. Its purpose was to find a method to predict the field behaviour of the roofing membrane from the mechanical properties of the materials used, and from the conditions at which the experiments were carried out. We had determined experimentally the relation between a certain % of elongation of the base, and the corresponding number of loads then can be applied. We knew also in

GRAPH 3

Bituminous N25-glassmat.

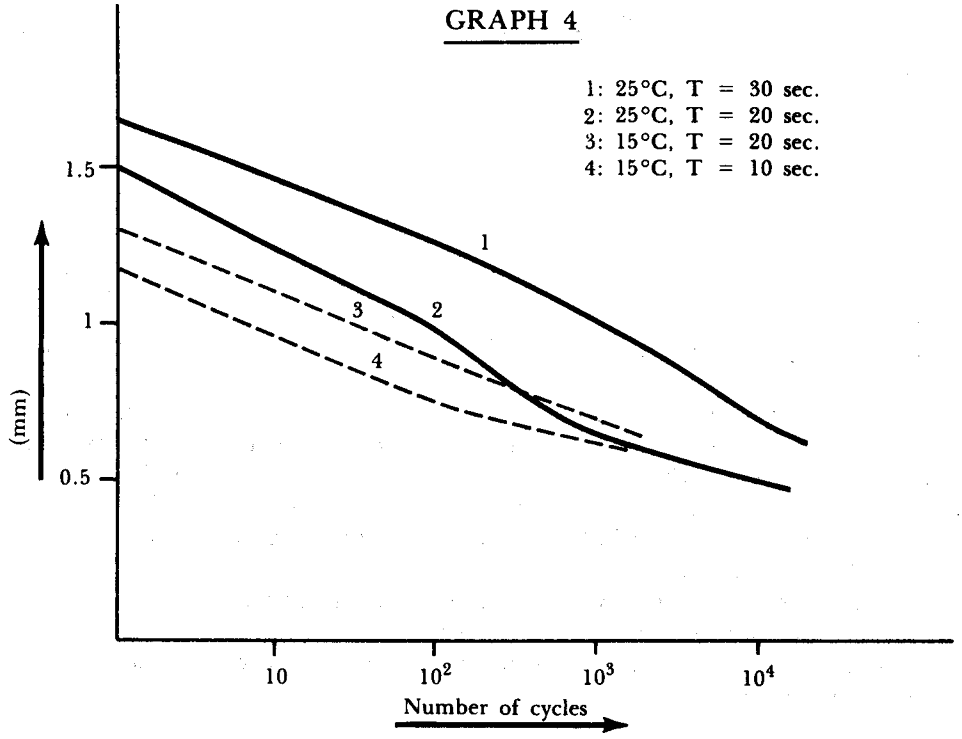


a single gap-opening movement how the stress in the base develops. But how, under field conditions, did the strain (or stress) develop in relation to the gap movement?

For the investigation of this problem we used a moving joint simulator. This apparatus consists of two metal plates with a slit in between, across which a piece of roofing material could be bonded with bitumen. Placed in a tensile tester, the metal plates can be moved with any desired speed, and to any desired slit distance. After some improvements the strain, induced in the base by the opening of the slit, could also be measured and recorded.

With this moving joint simulator roofing, materials have been repeatedly loaded at different temperatures and cycling times. The first experiments have been done with bituminous glassmat N.25 (Vitrix N.25). Results of these experiments are plotted in graph 4.

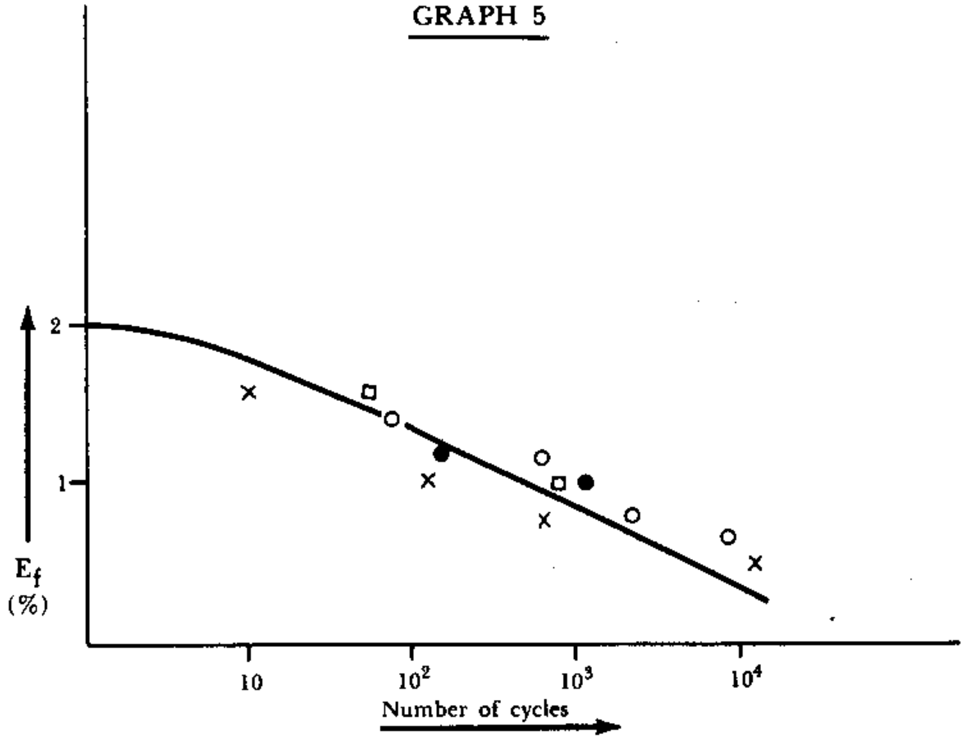
GRAPH 4



The relation between maximum gap amplitude g and the number of cycles that this amplitude can be applied, has been determined under 4 conditions of temperature and cycle-time (loading time), which means under 4 different stiffnesses of the bonding bitumen. Dr. Bonafont, of Ruberoid England has made a mathematical model to calculate from a certain gap movement the stress induced in the base-material. In this model corrections have been made for the form of the gap movement, which can be a sinusform, or of a triangular form. Rheological properties of the bitumen have also been taken into account because, due to the visco-elastic properties of the bitumen, some relaxation occurs.

With this mathematical model, the strain, as induced in the base material, was calculated in all four cases. These figures, plotted in graph 5, show a good agreement with the existing relation $E_f \longleftrightarrow N$.

GRAPH 5



Therefore, with this model it is possible now to calculate the fatigue endurance at conditions different from the experimental ones, and also for other base materials, with a known E-modulus.

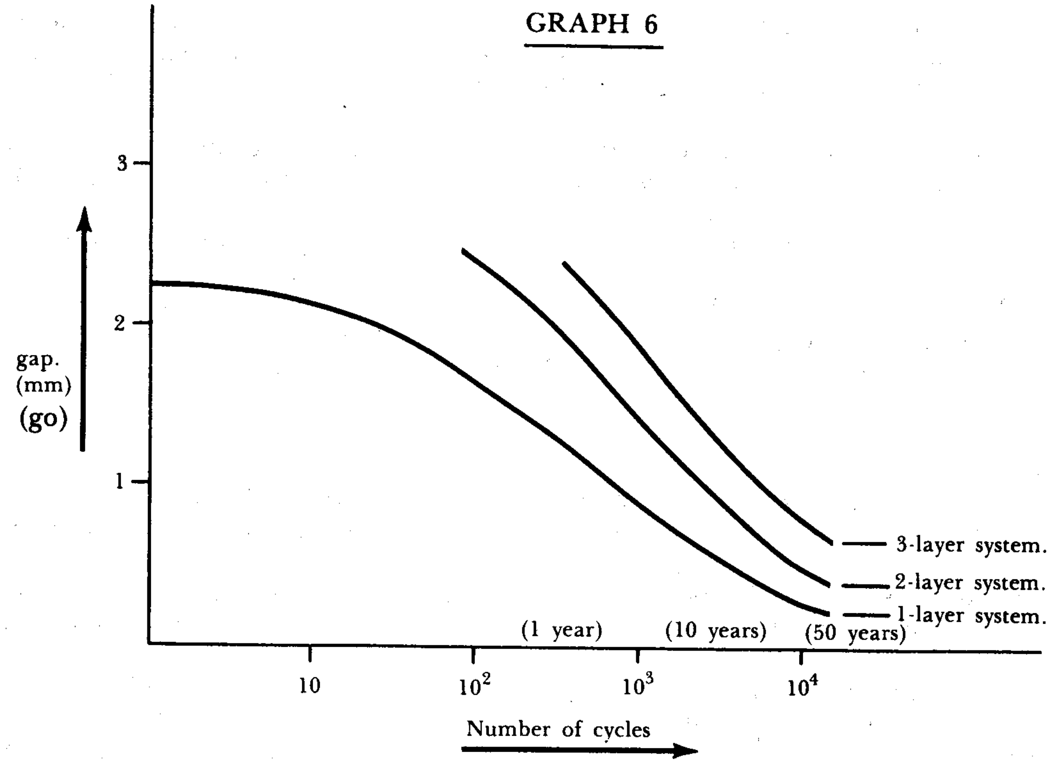
Fatigue-experiments on fresh bituminous ragfelt 330 have shown that its fatigue endurance is comparable with bituminous glassmat N.25.

Since the mathematical model for the fatigue-properties showed such a good agreement under different experimental conditions it has been further "modified" to calculate under actual conditions the fatigue behaviour of a roofing material. Therefore a correction has been made for the aging properties of the bitumen.

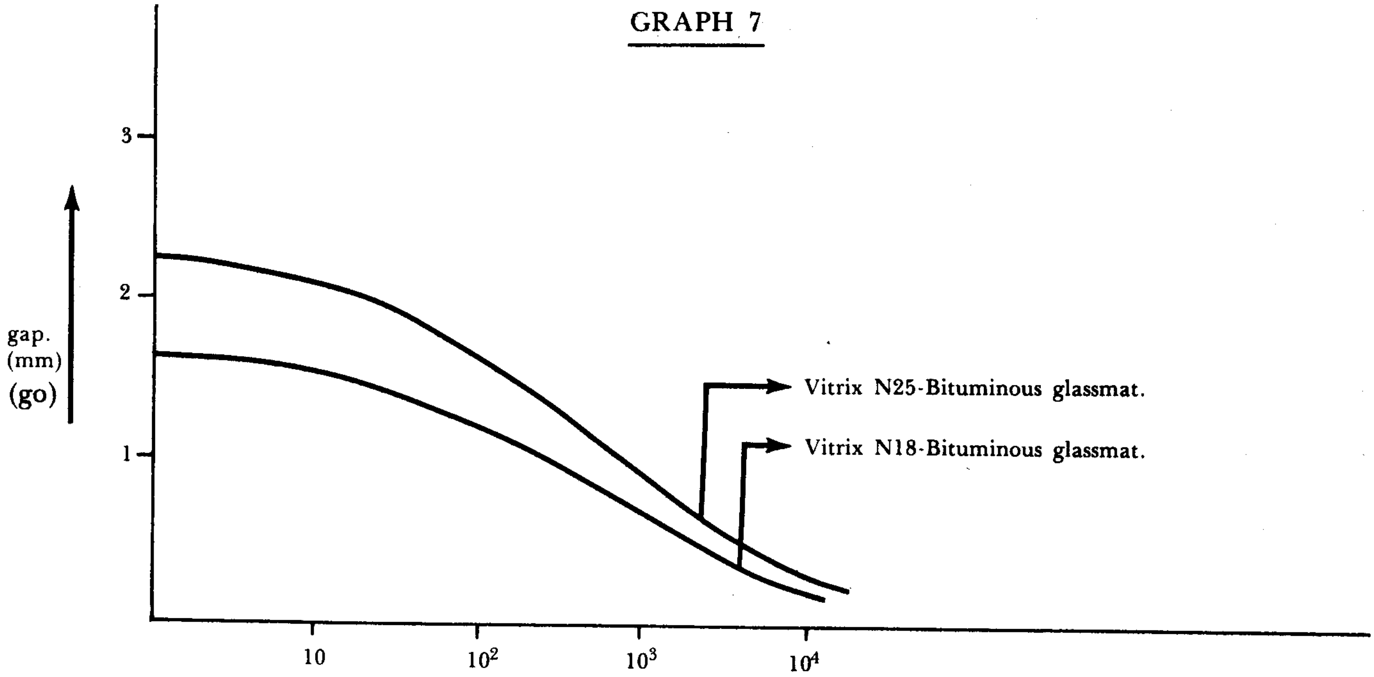
Some of the calculated data are presented in the next graphs. Graph 6 plots the fatigue properties of Vitrix N.25, fully bonded to a substructure, in case of a daily movement. In the calculation a loading time of 12 hours and a mean temperature of 10°C are assumed in this calculation.

In graph 7, a Vitrix N.25 has been compared with a weaker bituminous glassmat, of ca. 18 kfg/5cm; the difference in fatigue-endurance is distinctive. It is possible to extend the fatigue-endurance model to multi-layer systems. Calculated results of a two and three-layer system of Vitrix N.25 are also plotted in graph 6. Experimental figures are not yet available.

GRAPH 6



GRAPH 7



It is difficult to correlate fatigue-resistance theory with practical experience quantitatively. Yet, the theory is valuable in explaining how many factors play a role in roofing performance.

Thus far in this paper, the base has been the main subject. What about the bitumen? What type gives the best performance? The mechanical properties of bitumen depend on loading time and temperature. The extreme circumstance for roofing membranes are high temperatures, up to 80 or 90°C, and low temperatures, down to ca. 20°C. At high temperatures, the bitumen must still be stiff enough not to flow down a pitched roof. At lower temperatures, bitumen gets harder and stiffer. Higher stiffness means higher stress, induced in the base by movements of the substructure.

These two limits in practical conditions can be met by a bitumen with a softening point of about 100°C or higher, combined with a penetration of at least 30. For almost 20 years, we have used blown bitumen 110/30, as the one and only roofing bitumen. Other grades for all kinds of roofs in Holland, are bitumen 85/40 and 85/25. The last one has a higher stiffness at temperatures below ca. 35°C. At higher temperatures, both types may give problems when used on pitched roofs.

Another type of bitumen, marginally different from our 110/30, is the type 105/40, although it is not produced in Holland. The temperature susceptibility (P.I.) is about the same as for 110/30, but it has at all temperatures an even lower stiffness. This type is about the limit of blown bitumen, with respect to stability against phase-separation.

II.C. Aging of the bitumen.

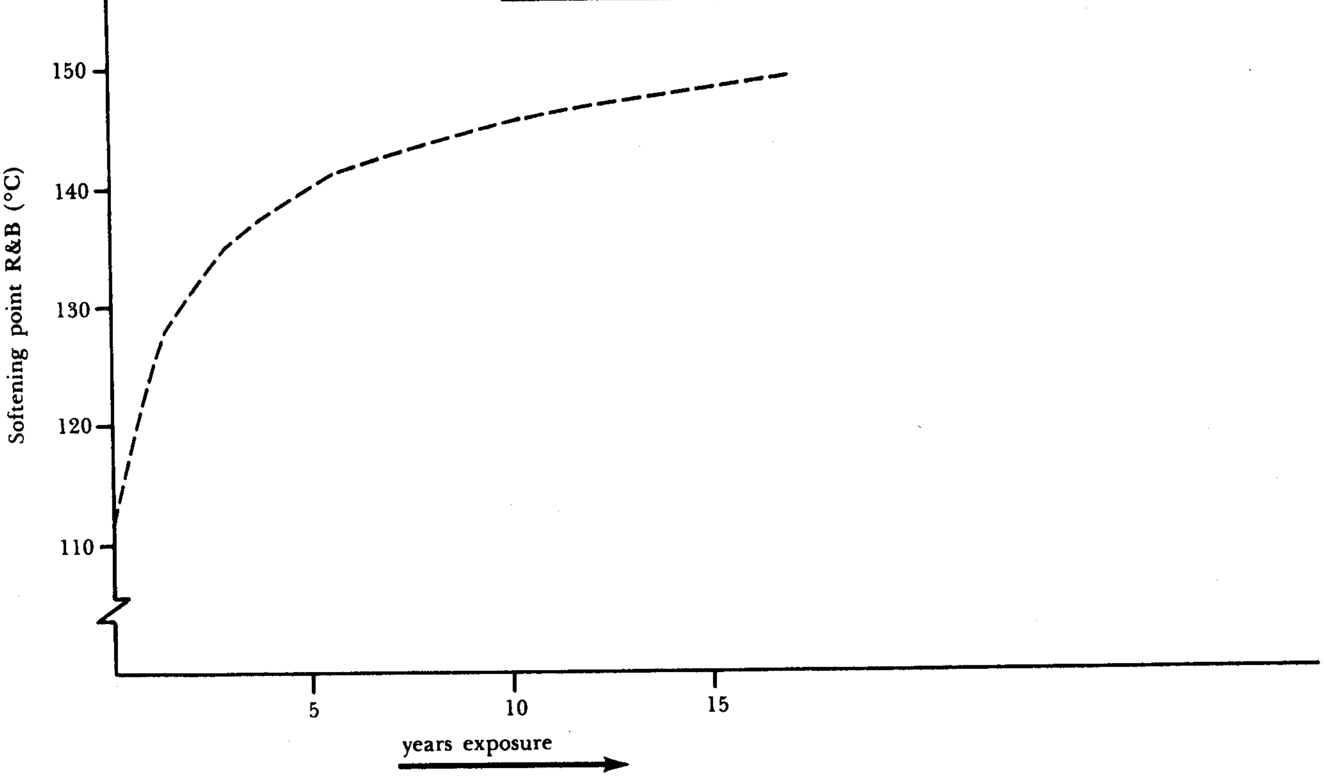
An important aspect to long term performance of roofing-membranes is bitumen aging which generally results in hardening, increased softening point R and B, and decreased penetration. In other words, the stiffness increases.

Aging has been studied extensively during the last 5 years by analysing samples taken from 1 to 20-year old roofs from several Western European countries. It was impossible to determine the effects of different climates and the influence of insulation.

The conclusion from the experimental work was that aging in practice takes place in about 15 years. The final result is then an increase in softening point of about 30%, and a decrease in penetration of about 50%. The rate of aging during the first few years is much faster than during the following years. Aging is best presented by a graph, plotting the softening point against age. The conclusion from Shell research on aging of 110/30 was that aging is mainly an oxidation reaction.

GRAPH 8

Aging of 110/30– Bitumen



Artifical aging (storage at certain temperature) has been carried out at different temperatures, up to 100°C. Heat-aging, whether at 40°C or at 100°C, involves the same reaction mechanism, an oxidation reaction, not an evaporation of lighter components.

Little is known yet, whether this is also true of bitumen from other oil sources. The high temperature stability (at ca. 180°C-200°C) can show large differences, depending on where and from what crude the bitumen is produced.

II.D. Glass-fibres.

The two commonly used types of glass for the production of glass fibres are the so-called A and E glass. Differences between these two types are their composition and consequently their properties. The difference in composition is the alkali-oxide content. A-glass has a roughly 14% higher content than E-glass. The E-glass was originally used specially for electrical purposes and has less than 0.8% alkalioxides. In contact with water, some of these alkali-ions can be exchanged for hydrogen-ions, leading to a different surface structure and imperfections. Because of the high surface/volume ratio of the glassfibres, this surface attack is greatly influenced by the fibre strength. By treating the glass with a suitable finish, this moisture sensitivity can be significantly reduced. E-glass has substantially higher tensile strength than A-glass - typically ca. 245 kg/mm^2 vs. 160 kg/mm^2.

Nevertheless, our practical experience indicates that glassmats from A-glass are not necessarily lower in quality.

The conclusion of this review may be that, although there is a lot to investigate further, the existing knowledge of bituminous roofing felts can be of important help in the selection of materials and products.

The development of glassmat N.25 and its finished product Vitrix N.25 has been proven to result in a high quality alternative to organic and asbestos roofing felts.