SERVICE LIFE PREDICTION OF FLAT ROOFS WITH POLYMER MODIFIED BITUMINOUS WATERPROOFING MEMBRANES
Service life prediction of flat roofs

A. TISO
DIC, UCLA - CONICIT; Venezuela
S. CROCE and E. DE ANGELIS
Dipartimento di Ingegneria dei Sistemi Edilizi e Territoriali, Politecnico di Milano; Milano, Italy

Durability of Building Materials and Components 8. (1999) *Edited by M.A. Lacasse and D.J. Vanier*. Institute for Research in Construction, Ottawa ON, K1A 0R6, Canada, pp. 1103-1113.

Abstract

The paper proposes a model for the prediction of flat roof service life based on the evaluation of the durability of the bituminous waterproofing membrane through accelerated thermal aging tests and its characterisation with Dynamic Mechanical Analysis (carried out with Rheometrics RDAII apparatus). Two different qualities of polymer modified (APP) bituminous waterproofing membranes were tested and these results have been used to measure performance level and to predict service life.
DMA tests on waterproofing membranes give information about the material's mechanical behavior that can be related to its molecular structure and can be further related to the basic decay process and kinetic reactions relationship. Using the results of accelerated thermal aging test of waterproofing membrane, Service Life can be calculated for each flat roof type and climate context.

Keywords: flat roof, waterproofing membranes, service life, thermal decay, durability of building materials, polymers modified bituminous membranes.

1 Durability and service life

Durability is generally assumed to be the ability of a building product to withstand weathering factors and to limit decay processes it can be subject to. This generic concept can be translated in something less general and more measurable that can be linked to the service life of the element or system the product is part of it.

If one wants to evaluate the service life of a critical system such as a flat roof, one can start with identifying the most probable failure modes. Then, one can set apart those failure modes that are brought about by design or construction or maintenance errors.

If one is able to identify the basic weathering mechanisms of its components that give rise to “non-pathological” failure modes of the system, then one can define a component’s durability in terms of its weathering resistance and one can evaluate the service life of the system as function of this resistance and, as well, the weathering action specific to context the component is subjected to.

The variations of a specific characteristic Z with time (t) can be modeled as linear function of a steady weathering action level C (as in the case of friction weathering) or as an exponential function of it (this is the case of certain mechanical characteristics of waterproofing membrane with thermal aging). In these cases one write:

linear model: $\Delta Z = \left(1/\mathrm{d}_C\right) \cdot \Delta t$ **(1)**

exponential model: $\Delta Z / Z_0 = \left(1/\mathrm{d}_C\right) \cdot \Delta t$ **(1 bis)**

Where: Z_0 is the initial characteristic value of the tested component; Z is the actual value of the characteristic value at general time t; $1/C$ is the decay rate of the characteristic Z in a generic environmental stress condition “C” (weathering factor level) and d_C its durability characteristic.

2 Service life prediction

Briefly, to predict the service life of a complex building system it is necessary: (1) to identify the failure modes; (2) to understand their qualitative and quantitative link with each decay process involved; (3) to model these elementary decay processes and find a relation with them and weathering factor levels.

The first and second point can be, in some way, resolved but the solution to the third point is not easily found through mere statistics. Natural decay process, in fact, can be longer than the life of the products studied on the market, hindering any feedback from field data in the prediction of decay processes. Indeed, innovation in the industry can produce better products (with lower natural decay rates) before one is able to evaluate the service lives of the first generation products.

Accelerated aging tests can be performed, but they have a fundamental limitation, that is, accelerated aging conditions cannot be easily related to in-service conditions. To overcome this problem, time transformation functions have to be identified, in order to relate accelerated weathering condition to in-service weathering conditions and, correspondingly, accelerated time to normal time. A time transformation function will be able to relate different weathering conditions to different time periods for the same amount of weathering. Infact, whatever model one chooses (linear, with eq. 1 or exponential, with eq. 1 bis), one can write the following equivalence:

$$\Delta t = \frac{\mathrm{d}_C}{\mathrm{d}_{C'}} \cdot \Delta t' = K_{C-C'} \cdot \Delta t' \qquad \textbf{(2)}$$

Where: $K_{C\text{-}C'}$ is the time transformation function from the C to the C' weathering factor level.

Then we can generalise previous equation and write the following expression for the evaluation of service life, on the basis of a time transformation functions:

$$SL = K \cdot t_{AST} \tag{3}$$

Where: *SL* is the predicted Service Life; t_{AST} is the time-to-failure, measured in a standard accelerated weathering conditions (defined for the specific failure mode); *K*, is the time transformation function that relates accelerated decay rate to the decay rate produced by average local conditions (for a non-protected product exposed to local micro climate).

3 Waterproofing membrane characteristics and flat roofing service life

The case of flat roofs and polymer-modified bituminous waterproofing membranes is straight forward, as the principal failure mode of the first is the failure of the waterproofing membrane (water infiltration through it) and it is normally connected, in non-pathological cases, to one weathering factor: bituminous compound embrittlement by thermal aging, i.e. an embrittled membrane is no longer capable withstanding normal mechanical stresses.

The nature of polymer-bituminous compound, in fact, makes the membrane very sensitive to thermal exposure: chemical reactions of the compound induced by thermal energy reduce the mobility between molecular chains and induce a growth in internal cohesion forces. This change in its micro-structure generates changes in the mechanical behavior of the compound (i.e. glass transition temperature increases) and consequently, alters the performance of the membrane. If one assume that the ageing decay rate will follow an exponential Arrhenius relationship:

$$1/\mathrm{d}_C = A \cdot \exp(-B/T) \tag{4}$$

Where: *A* (h^{-1}) is a constant referred as the material failure mechanism; *T* (°K) is the weathering factor level (thermal stress condition); *B*=*E/k* (°K) is a fixed value related to the composition of the material and the specific thermal induced decay reactions, where *E* is the thermal energy of activation of the reaction and *k* is Boltzmann's constant.

Then, the time transformation function from standard test conditions (T_{test}) to average in-service conditions (*T*) can be written as:

$$K = \frac{A \cdot \exp(-B/T_{test})}{A \cdot \exp(-B/T)} = \frac{\exp(-B/T_{test})}{\exp(-B/T)} \tag{5}$$

4 Modeling of thermal stress

Waterproofing thermal exposure is related to local weather conditions and to roof layer sequence, as they can provide more or less thermal protection to the membrane, because of their construction sequence. Thermal decay rate has been expressed as a function of temperature (4). As temperature is constant only in thermal aging tests, and in-service conditions are characterised by variable temperature cycles due to the weather conditions, we have to find a significant temperature value.

Temperature can be generally assumed as a periodical variable and expressed as a function of some parameters. The following equation is proposed:

$$T(t) = \overline{T}_y + 0{,}5 \cdot \Delta T_a \cdot \left(1 - \cos\left(\pi \cdot t/4380\right)\right) + 0{,}5 \cdot \Delta T_{d(t)} \cdot \left(1 - \cos\left(\pi \cdot t/12\right)\right) \qquad \textbf{(6)}$$

Where: t is the time in hours; $\overline{T}_y$, is the mean yearly air temperature; ΔT_a, is the difference between the maximum (summer) and minimum (winter) mean daily temperature, in an annual cycle; $\Delta T_{d(t)}$ is the daily temperature difference, that changes in accordance with the seasons. The amplitudes of the two periodical components can be expressed as:

$$\Delta T_{d(t)} = 0.5 \cdot \left(\Delta T_{dS} + \Delta T_{dW}\right) - 0.5 \cdot \left(\Delta T_{dS} - \Delta T_{dW}\right) \cdot \cos\left(\pi \cdot t / 4380\right) \qquad \textbf{(7)}$$

$$\Delta T_a = \Delta T_T - \Delta T_d \qquad \textbf{(8)}$$

$$\Delta T_T = \Delta Ts_{\max} - \Delta Tw_{\min} \qquad \textbf{(9)}$$

Where: ΔT_{dS}, is the difference between the maximum and minimum hourly temperature in a standard summer day; ΔT_{dW}, is the difference between the maximum and minimum hourly temperature in a standard winter day; ΔTs_{max}, is the maximum value of average hourly temperature in summer; Tw_{min}, is the minimum value of average hourly temperature in winter; ΔT_d, is the mean difference between ΔT_{dS} and ΔT_{dW}.

Based on the above relations, a frequency distribution series can be calculated to given temperature intervals, given by the percentage of the hours in a yearly cycle.

To be able to generalise the application to any thermal condition a membrane might be subjected to, the temperature distribution is related to $\Delta T_d / \Delta T_T$; in this regard, the results of the percentages of hours in a year are shown in Table 1.

Table 1: Frequency distribution in percentages of hourly temperatures that can be registered from Tw_{min} to Ts_{max} in a annual cycle, assuming a sinusoidal daily and yearly variation of the temperature values in function of ΔT_d and ΔT_T.

Temperature Intervals			DT_d /DT_T										
From		***To***	***0***	***0.1***	***0.2***	***0.3***	***0.4***	***0.5***	***0.6***	***0.7***	***0.8***	***0.9***	***1***
$Tw_{min}+0.9DT_T$	fi	Ts_{max}	25	15	8	7	6	6	6	5	7	8	21
$Tw_{min}+0.8DT_T$	fi	$Tw_{min}+0.9DT_T$	0	10	11	6	5	6	6	6	7	14	8
$Tw_{min}+0.7DT_T$	fi	$Tw_{min}+0.9DT_T$	17	12	14	13	9	7	5	9	10	10	8
$Tw_{min}+0.6DT_T$	fi	$Tw_{min}+0.7DT_T$	0	6	8	9	10	8	9	8	11	9	8
$Tw_{min}+0.5DT_T$	fi	$Tw_{min}+0.6DT_T$	8	5	7	11	14	12	10	11	10	8	4
$Tw_{min}+0.4DT_T$	fi	$Tw_{min}+0.5DT_T$	8	11	9	6	8	14	14	14	9	8	4
$Tw_{min}+0.3DT_T$	fi	$Tw_{min}+0.4DT_T$	0	0	3	10	13	11	20	14	12	8	8
$Tw_{min}+0.2DT_T$	fi	$Tw_{min}+0.3DT_T$	17	17	14	8	10	16	12	14	12	10	8
$Tw_{min}+0.1DT_T$	fi	$Tw_{min}+0.2DT_T$	0	0	6	12	15	11	9	10	13	12	8
Tw_{min}	fi	$Tw_{min}+0.1DT_T$	25	25	20	16	11	9	8	9	9	14	21

After this, we can use equation (5) to evaluate *K*, assuming that the total effect of the thermal decay rate as the addition of each effect in the decay rate given by each step of thermal level. So, we have an expression that can be used along with the values given by Table 1, with each percentage and temperature value:

$$K_T = \frac{\exp\left(-B/T_{test}\right)}{\sum_{i=1}^{n} \frac{\%_i}{100} \exp\left(-B/T_i\right)} \qquad \textbf{(10)}$$

Where: $\%_i$ is the percentage of hours in a annual cycle at determinate temperature values; T_i, is the nominal temperature value related to every interval, and it can be assumed with the value of the maximum limit superior of the temperature interval.

5 Dynamic mechanical analysis (DMA)

As mentioned before, waterproofing membrane is the most critical component of a flat roof systems and thermal decay is the principal bituminous membrane alteration process. Any bituminous blend or composite is characterised by a temperature range in which the material is considered performing. The uppest limit of this range is the hottest temperature without excessive softening of the compound (it can be evaluated with the ring & ball test as it is usually done for bituminous blend) and it is usually evaluated through the ring & ball test. The lower limit - the coldest temperature at which the membrane can maintain good flexible behavior - is usually evaluated through the cold bending membrane standard test, an empirical test which shows the coldest temperature at which it can bend in a predetermined cylinder without cracking.

As these tests evaluate actual membrane behavior, the assessment of its durability is usually carried out measuring cold bending temperature evolution after different accelerated thermal aging periods tests at constant temperature exposition (70°C). Smaller changes of this characteristic between aged and unaged samples means longer waterproofing membrane durability. Nevertheless, this evaluation does not give information about the micro-structural conformation of the material and the fundamental failure mechanisms cannot be modeled to forecast decay rate.

Research is dealing with new testing methodologies, as for instance the Dynamic Mechanical Analysis (DMA) applied to waterproofing membrane thermal aging: this test, in fact, can provide information about the mechanical behavior of the compound over a large range of temperatures and more precise data about the variations of the thermal-mechanical characteristics against the fundamental changes in the material's micro-structure, that can be used more effectively to evaluate waterproofing durability and roof systems service life.

DMA tests consist of torso-deformation cycles of load on material samples to evaluate the characteristics of viscous-elastic-plastic response of the submitted material at a determined frequency. It provides the values of "storage shear module" G' and "dynamic shear module" G". The first is related to the potential energy that is stored as a mechanical response of the material, while the second one is related to the energy that is dissipated by heat. From the ratio of these material's modules (G"/G') the material's damping is given, this characteristic is related to the material's micro-structure and the relative mobility between molecular chains in the material.

Carrying out DMA over a wide range of temperature values, with the help of a thermal cell and temperature control systems (available in Rheometrics RDII apparatus used in standard test for plastic materials) one can obtain a series of damping-temperature curves for various waterproofing membranes. These damping-temperature values provide interesting and useful information about the thermal-mechanical behavior of waterproofing membrane; changes in damping values after aging can be easily related to decay reactions and weathering process of the material.

6 Experimental decay rates of waterproofing membranes

A series of experimental program tests were carried out based on accelerated thermal aging of polymer modified bitumen waterproofing membranes: the aim was the experimental evaluation of the changes of mechanical characteristics of the membrane generated by thermal exposure.

Two different qualities of polymer modified bituminous waterproofing membrane have been tested. The first type of waterproofing membrane (n.1) had a minimal amount of polymers and poor reinforcement, whereas the second one (n.2) was richer in polymers and better reinforced.

Table 2: Values of the characteristics of waterproofing membrane over different lengths of time of thermal ageing, and the respective decay rates and correltion parameters with respect to their tendency to follow an exponential model

Membrane 1	**Days of ageing at 70°C**				**decay**	**parameter**
Tests	**0 d.**	**28 d.**	**90 d.**	**180 d.**	**rate**	**R^2**
Cold Bending (°C)	0	10	15	25	0,0084	0,754
Softening Point Blend (°C)	143,0	143,5	146,0	146,0	0,0001	0,7869
Max. Tens. Strength Long. (N)	471	612	759	648	0,0015	0,3698
Max. Elongation Long. (%)	28	8	5	5	-0,0079	0,5951
Damping at 0°C (adim.)	0,34	0,29	0,23	0,20	-0,0029	0,9328
Damping at 20°C (adim.)	0,38	0,35	0,28	0,24	-0,0026	0,9701
Membrane 2	**Days of ageing at 70°C**				**decay**	**parameter**
Tests	**0 d.**	**28 d.**	**90 d.**	**180 d.**	**rate**	**R^2**
Cold Bending (°C)	-15	-10	-5	5	0,0081	0,9038
Softening Point Blend (°C)	152,0	152,0	152,0	153,0	0,0000	0,7777
Max. Tens. Strength Long. (N)	824	861	868	812	-0,0001	0,1269
Max. Elongation Long. (%)	48	41	41	40	-0,0008	0,5128
Damping at 0°C (adim.)	0,28	0,22	0,20	0,20	-0,0017	0,6643
Damping at 20°C (adim.)	0,30	0,25	0,22	0,22	-0,0016	0,7416

Standard and DMA membrane tests were performed on submitted unaged and aged samples of both materials, after 28, 90 and 180 days of accelerated thermal aging at 70 °C (UNI-8202/27). The results of these tests for both materials are shown in Table 2. Moreover the decay rate and its correlation parameter (R^2) are included, both calculated according to an exponential tendency curve of the respective characteristic vs. time.

In accordance with the results of standard tests, membrane n. 2 can be considered more durable than membrane n. 1, as the first shows lower changes in the values of its Cold Bending Temperature against thermal aging.

First results confirm that an exponential model can be proposed for thermal decay process of polymer modified bituminous membranes. In absence of any time-transformation function, the values of d_C should only be obtained empirically from field experiences. In this sense, results taken from standard accelerated thermal aging tests at constant temperature of 70 °C can be used to calculate the decay rate of the respective characteristics of the waterproofing membranes studied and the parameters used into the model considering the parameters when they are in service.

7 Roof service life prediction

Equation n.3 can be used to estimate the service life of a roof waterproofing system. We have applied this method to two different roofs in different localities: Milan (45°N) and Maracaibo (10° N). Input data and results are shown in Table 3, for the following roofs:

1. unprotected membrane in a 20 cm thick concrete roof deck, without insulation.
2. unprotected membrane in a 20 cm thick concrete roof deck, 5 cm layer insul.
3. protected waterproofing in a 20 cm thick concrete roof deck, 5 cm layer insul.
4. inverted roof with waterproofing membrane located under 5 cm insulation over a 20 cm thick concrete roof deck.

The distribution of temperatures for the different exposure of the membrane analyzed in the examples are showed in Table 4 (Milan) and Table 5 (Maracaibo) based on the distribution given by table 1. Taking as a reference the experimental results of tests on membrane 1 (which showed a higher decay degree and lost its main characteristics over 180 days of thermal aging testing at constant temperature of 70°C) we calculated *K* using Eq. 9 for the different types of roof, assuming B= 8,000 K. With these values of *K*, we calculated the expected service life of the different roofs, which are shown in Table 6.

8 Conclusions

The results obtained confirm the importance of controlling thermal exposure and the durability performance of the membrane for a longer roof service life; especially for site conditions characterised by high temperature peaks and hig solar irradiation.

The model presented can give only an indication of the expected service life of a roof, through analysis of thermal decay rates. Nevertheless, these results can be useful used in building design and planning when service life expectancy data is not available. Further investigation is required in order to obtain a more accurate prediction; but this may not be useful for standard applications.

Table 3: Application of two locations of different latitude in calculating the relationship $\Delta T_d/\Delta T_T$ to the membrane temperature values as a function of the roof technologies

Site	*Year Period*	*Temp. Values*	*Roof Type 1*	*Roof Type 2*	*Roof Type 3*	*Roof Type 4*
Milan	Coldest month,	Tw_{max} (°C)	10	10	8	15
Lat.: 45° N	*winter* (January)	Tw_{min} (°C)	0	-3	0	15
		DT_{dw}(°C)	10	13	8	0
	Hottest month,	Ts_{max} (°C)	52	60	50	23
	summer (June)	Ts_{min} (°C)	22	19	23	22
		DT_{ds} (°C)	30	41	27	1
		$DT_d = (DT_{dw}+DT_{ds})/2 =$	20	27	17	1
		$DT_T = Ts_{max} - Tw_{min} =$	52	63	50	8
		$DT_d/DT_T =$	***0.38***	***0.43***	***0.34***	***0.13***
Maracaibo	Coldest month,	Tw_{max} (°C)	55	65	53	25
Lat.: 10° N	*winter* (January)	Tw_{min} (°C)	25	23	25	24
		DT_{dw}(°C)	30	42	28	1
	Hottest month,	Ts_{max} (°C)	60	72	58	25
	summer (June)	Ts_{min} (°C)	28	26	28	24
		DT_{ds} (°C)	32	46	30	1
		$DT_d = (DT_{dw}+DT_{ds})/2 =$	31	44	29	1
		$DT_T = Ts_{max} - Tw_{min} =$	35	49	32	1
		$DT_d/DT_T =$	***0.89***	***0.88***	***0.90***	***1.00***

Table 4: Assumed membrane temperature frequency distribution of the different types of roofs in the city of Milan (Lat. 45° N), according to the application of the values given by tables 2 and 3

Roof Type 1		***Roof Type 2***		***Roof Type 3***		***Roof Type 4***	
$DT_d/DT_T = 0.38$» 0.4		$DT_d/DT_T = 0.43$» 0.4		$DT_d/DT_T = 0.34$» 0.3		$DT_d/DT_T = 0.13$» 0.1	
T_i (°C)	$\%_i$	T_i (°C)	$\%_i$	T_i (°C)	$\%_i$	T_i (°C)	$\%_i$
$Ts_{max} = 52$	6	$Ts_{max} = 60$	6	$Ts_{max} = 50$	7	$Ts_{max} = 23$	15
46.8	5	53.7	5	45.0	6	22.2	10
41.6	9	47.4	9	40.0	13	21.4	12
36.4	10	41.1	10	35.0	9	20.6	6
31.2	14	34.8	14	30.0	11	19.8	5
$T_{med} = 26.0$	8	$T_{med} = 28.5$	8	$T_{med} = 25.0$	6	$T_{med} = 19.0$	11
20.8	13	22.2	13	20.0	10	18.2	0
15.6	10	15.9	10	15.0	8	17.4	17
10.4	15	9.6	15	10.0	12	16.6	0
5.2	11	3.3	11	5.0	16	15.8	25
$Tw_{min} = 0$		$Tw_{min} = -3$		$Tw_{min} = 0$		$Tw_{min} = 15$	

Table 5: Assumed membrane temperature frequency distribution of the different types of roofs in the city of Maracaibo (Lat. 10° N), according to the application of the values given by Tables 2 and 3

Roof Type 1		*Roof Type 2*		*Roof Type 3*		*Roof Type 4*	
$DT_d/DT_T = 0.89$» 0.9		$DT_d/DT_T = 0.88$» 0.9		$DT_d/DT_T = 0.90$		$DT_d/DT_T = 1.0$	
T_i (°C)	$\%_i$	T_i (°C)	$\%_i$	T_i (°C)	$\%_i$	T_i (°C)	$\%_i$
$Ts_{max} = 60$	8	$Ts_{max} = 72$	8	$Ts_{max} = 57$	8	$Ts_{max} = 25$	21
56.5	14	67.1	14	53.8	14	24.9	8
53.0	10	62.2	10	50.6	10	24.8	8
49.5	9	57.3	9	47.4	9	24.7	8
46.0	8	52.4	8	44.2	8	24.6	4
$T_{med} = 42.5$	8	$T_{med} = 47.5$	8	$T_{med} = 41.0$	8	$T_{med} = 24.5$	4
39.0	8	42.6	8	37.8	8	24.4	8
35.5	10	37.7	10	34.6	10	24.3	8
32.0	12	32.8	12	31.4	12	24.2	8
28.5	14	27.9	14	28.2	14	24.1	21
$Tw_{min} = 25$		$Tw_{min} = 23$		$Tw_{min} = 25$		$Tw_{min} = 24$	

Table 6: Predicted service life for both waterproofing membranes, calculated as a function of the different conditions of assumed thermal exposure

Thermal Context	*Milan: Lat. 45° N* T_{min}*(air): 0°C.*				*Maracaibo: Lat. 10° N* T_{min}*(air): 20°C.*			
Reference Material Characteristic	*Membrane Damping at 0°C*				*Membrane Damping at 20°C*			
Technological Choice	***Roof 1***	***Roof 2***	***Roof 3***	***Roof 4***	***Roof 1***	***Roof 2***	***Roof 3***	***Roof 4***
Calculated parameter, K_T^*	***16.73***	***10.74***	***17.38***	***55.13***	***5.12***	***2.69***	***6.06***	***35.96***
S.L. Membrane n. 1 (years)	8.25	5.30	8.57	27.19	2.82	1.48	3.33	19.78
S.L. Membrane n. 2 (years)**	14.07	9.04	14.62	46.38	4.57	2.41	5.42	32.14

* *Calculated by equation 5 with temperature and percentage values given by Tables 4 and 5.*
** *Calculated by relations of the reference characteristic decay rates shown in table 2.*

9 References

Ang Aik Leng. "Prediction of the Remaining Service Life of Roofs: An Exponential Mathematical Model". Architectural Science Review, Vol. 34, September, 1991.

Cash C. "Estimated Mean Temperatures of Horizontal Surfaces for Predicting the Durability of Thermally Sensitive Materials (Arrhenius Relationship)". Proceeding of Dealing with Defects in Buildings. Varenna, Italy, September, 1994.

CIB & RILEM "Thermal Analysis Testing of Roofing Membrane Materials". Final report of the Thermal Analysis Task Group RILEM 120-MRS/CIB W83. March, 1995.

Gaddy G., Rossiter W., Eby R. “The Applicability of Modern Analytical Techniques to Detection of Changes in Roofing Membrane Materials brought about by Heat Aging”. Proceeding of International Waterproofing Association. Amsterdam, 1995.

Nelson W. “Accelerated Testing: Statistical Models, Test Plans, and Data Analyses”. John Wiley & Sons, 1990.

Oba K., Partl M.N. “Durability of Polymer-Modified Bituminous Roofing Membranes”. Proceeding of Durability of Building Material & Components. Vol. II. Stockholm, Sweden, 19-23 May 1996.

Ozkan. “Temperatures Attained in Naturally Weathered Waterproofing Membranes Used for Roofing”. Architecture and Building Science-King Saud University, Riyadh. Architectural Science Review, Vol. 34, March, 1991.

Tiso A., Di Landro L., Pagano M. “Stima della durabilitá di membrane impermeabilizzanti in bitume-polimero”. I Convegno Nazionale sulla Scienza e Tecnologia dei Materiali. Lerici, Italia, Aprile, 1997.

Tomiita T. “Solar UV, Wetness and Thermal Degradation Maps in Japan”. Proceeding of the Fifth International Conference of Durability of Building Materials. Brighton, UK, 7-9 November 1990.