7th CONFERENCE ON ASPHALT PAVEMENTS FOR SOUTHERN AFRICA

THE USE OF FOAMED BITUMEN IN FULL-DEPTH IN-PLACE RECYCLING OF PAVEMENT LAYERS ILLUSTRATING THE BASIC CONCEPT OF WATER SATURATION IN THE FOAM PROCESS

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Abstract

This fast track recycling technique has become available in South Africa and this paper focuses on the use of foamed bitumen to improve natural aggregate and gravels for road works in particular for rehabilitation purposes. Full depth recycling is a rehabilitation technique in which the surfacing of a pavement section and a predetermined portion of the underlying materials are uniformly broken down, pulverized or blended and stabilized to form a new constituted base and / or subbase. The use of foamed bitumen and a small percentage of lime and cement in a single process employing deep in-situ mechanical recycling machines, provide economical solutions for the rehabilitation of deteriorated road pavement layers. The stabilizing techniques and equipment have developed to such a level that all the existing materials can be utilised without the addition of new masterials.

The following foaming systems are currently available in order they developed:

- The Mobil system
- The Scandinavian system., (Nesotec OY / Finland)
- The Savalco system ,Sweden (combination of Mobil and Ladis Csanyi), and
- New “Home Made” systems

The authors are presenting the early findings of research into the technical differences between the first and the third systems and proposals of how to optimize the characteristics of each system.
Under South African conditions it was found that the Scandinavian system some times gave better results than the Mobil system for a given material, so every one of these systems clearly has a unique field of application.
Project details (Mobil/ Scandinavian/Savalco) are provided on works undertaken mainly for the Free State Provincial Works and Roads Department in South Africa.

1. GENERAL

1.1 History of the Foaming Systems

The art of manufacturing foam bitumen has a long and colourful history which dates back to 1889.

C In 1889 in Nebraska USA, in full depth repairs, bitumen was added to base course materials to improve the bearing capacity.
C The second break through came in 1928, when August Jacobi from Darmstadt Germany produced and patented the first his hot bitumen foaming systems.
C The Third break through came in 1957, when Prof. Ladis Casanyi of Iowa State University, demonstrated the addition of foam bitumen to marginal quality aggregates. He used a system where steam under pressure was introduced into hot bitumen. In practice it was found to be totally impractical due to the complexity of his equipment and the inability to control the amount of steam that was added. He patented the method for combining bituminous binder with an aggregate material.
C The fourth break through came in 1971 when Mobil Oil Corporation patented their foaming system in Australia. After years of research in the late sixties and the early seventies the process was modified by Mobil, the steam was replaced with cold atomized water (between 1.5% and 2.5% of cold water). The water was injected under high pressure into the pressured hot bitumen in a specially designed expansion chamber, the foam bitumen that was produced was then sprayed through nozzles onto cold unheated, damp aggregate which were then mixed to produce foamed stabilised material.
C After the Mobil's patent rights expired in 1991, many new foaming systems were developed world-wide.
• The Scandinavian system , Nesotec OY 1994 a new generation system was developed by Nestor Salminen, this was followed by Savalco Sweden and other "Home Made" systems
C Currently foamed bitumens are used in many countries (i.e. South Africa, Africa, Australia, Canada, Mexico, Europe, Middle East and the Scandinavian countries).

1.2 Foaming processes

There are two basic foam processes available to date:

C Mobil process (1928 and 1971), currently, a foaming process.
C Refined/reformulated process that was developed by Nesotec in 1994, a water saturation process
C Other systems have been developed but fall outside the scope of this report.

2. PAST EXPERIENCE

Experience has shown in practice that foamed bitumen from the Mobil process is not a homogeneous material but consists of the following four substances:

- C Cold water (unreacted)
- C Steam (unreacted)
- C Bitumen (unreacted)
- C Foamed bitumen

3. FOAMED BITUMEN

Foamed bitumen is formed when superheated steam (temperature higher than 120° C) is introduced into hot bitumen in the thin film state to form covalent bonds, which foams and when the foaming stops, 25 seconds later to produce a product which can be described as water saturated bitumen. Bitumen in this form is not an emulsion nor is it a cutback bitumen although chemical additives may have been added to soften and enhance foaming as is mentioned in the modified Mobil process by Lewis et al(3). This is not a chemical but a physical chemical process. The moment the water is driven off it reverts back to the original bitumen. Whether all the water in practice can be driven off with normal processes is still highly debatable.

The foamed bitumen in this state of water saturation opens another perspective on its field of application, using the above physical state of the bitumen. In this state the water saturated bitumen is, for all practical purposes, stable. Normal day temperature and low humidity are not sufficient to drive off the water from this state by evaporation. It requires more energy as described in the following paragraphs.

3.1 Application of pressure to remove the free water

This is done in the rolling process during construction compaction i.e. through pressure and suction forces. If a lightly trafficked road with a well developed aggregate frame is being treated in this manner this force may be sufficient.

3.2 Pressure and chemical forces to remove the free water

Under heavily trafficked roads it may be advisable to add some cement to aid the loss of some water through the chemical reactions of the cement and the van der Waal forces in the early stages of the process. However, the water absorption of the material to be mixed with the foamed bitumen may require stringent control of the extra water added to aid the milling process. This will depend on the in-situ moisture condition, water absorption and water adsorption characteristics of the given materials to be treated.

4. THE ROLE OF WATER ABSORPTION, ADSORPTION AND OTHER PROCESSES

4.1 The role of water absorption

This will vary between the materials encountered or proposed on a given site. The state of weathering that has taken place in the material and the particle size distribution of the material to be treated with water saturated bitumen also plays a major role in the stabilizing process.

As the water phase of the water saturated bitumen is utilized to satisfy the water absorption characteristics of a particular gravel, the amount of free water available in the water saturated bitumen and the amount of water that has been absorbed by the material plays a vital role in the stabilizing process.

In practice the optimum moisture content in some materials may vary considerably between the water absorption of the coarse and the fine material fractions of the matrix to be treated. The coarse material fraction may be coated with a film of water while the fine material may be under optimum.

It is well known that bitumen does not disperse into water. Therefore it does not adhere to wet surfaces with a coating of free water. This characteristics can be overcome with a wetting agent to some degree.

As the finer particles are under optimum the water phase of the covalent bonds of the water saturated bitumen can be activated to coat the fines to form a mastic (as defined by Salminen) to bond the material. From this it will be come clear that the coarse particles should be under optimum for this process as well.

4.2 The role of water adsorption

This phenomenon may be described as water held in surface tension on the surface of the aggregate fractions (both coarse and fine aggregate). The shape and the size of the aggregate and the surface texture play a major role in the amount of water that can be held.

The amount of water that can be held in this phase is dependent on the state of weathering of the aggregate and is measured as water absorption. The pore size and the pore structure of the aggregate will determine whether the absorption is time dependant (short or long term absorption).

If the aggregate is in a too dry state the surface may be too dusty, which will cause the water saturated bitumen to “ball up” and forming bitumen nodules in the dusty matrix. This problem can be overcome by prewetting i.e. the surface tension of the water is increased to enable the water saturated bitumen to adhere to the surface of the material, through a process similar to osmosis (diffusion). The water phase of the water saturated bitumen is absorbed in to the pores of the aggregate (this process is time dependent). The level of impregnation and thus the level of the coating that can be achieved is controlled by the percentage of water absorbed by the aggregate before coming into contact with the water saturated bitumen. The viscosity of the binder (addition of softeners), the size of the pores and the pore structure (long term absorption) control the thickness of the coating and the amount of binder that is available in the mixture i.e. the "mastic" as defined by Salminen (6).

However, in a saturated state no additional water can be accommodated in the adhesion phase and no coating or "mastic" formation on the aggregates is possible by the water phase of the water saturated bitumen. The percentage of water absorbed by the aggregate therefore plays a major role in the adhesion and the coating that is achieved, especially the coating (or "mastic") that is achieved on the larger particles.

4.3 **Problems that can be anticipated with unbalanced bitumens**

If the texture or the matrix of the aggregate or gravel particles is such that the pore sizes are very small but high in porosity (e.g. blotting paper), and if there is any $Ca(OH)_2$ or $Mg(OH)_2$ which is soluble in the aromatic oils and because of the dispersion of the Ca^{++} or the Mg^{++} in this medium, the risk of structural disintegration of the binder exists (Shell Qualigon Test). This is a very slow process.

If the water phase of the water saturated bitumen is in contact with such a "blotting paper" surface, it will lead to the scraping off of the smaller molecules of the bitumen (aromatic and paraffinic fractions) leaving unbalanced bitumen with too many medium and large molecules in it. This new bitumen that is formed is hard, brittle and it will strip the moment it comes into contact with water. A softer grade of bitumen can be used to overcome this problem.

However this condition must not be confused with, the condition when lime or cement is added to bitumen treated materials. The lime or the cement that is added forms part of the molecular structure (soluble portion) of the bitumen (after Yen's postulation) and this leads to the increase of the stiffness of the bitumen. The higher viscosity of the filler enriched bitumen will therefore lead to a thicker coating ("mastic" formation) around the aggregate or gravel particles with less risk of stripping.

The natural fines of some gravels (e.g. calcretes) may have a similar effect as with cement or lime on the bitumen that assist in increasing the viscosity of the bitumen and therefore the thickness of the coating. In cases like this the bitumen must be stable, as well as balanced, and softeners or additives that would enhance the foaming can be used. If the aggregate is porous and the moisture regime and the percentage binder required for coating are optimized, by allowing for sufficient space in the unfilled pores or in the pore structure for the water phase of the water saturated bitumen to be absorbed by design, this stabilized material will continue to improve with time, enhancing the durability of the foamed bitumen matrix. Calcretes can also first be treated with lime, foamed and then cement can be added to remove the free water.

4.4 The role of temperature during the milling and the mixing stage

In order to produce a homogeneously treated material matrix utilizing the water saturated bitumen phase, the most important factor is the coating that is achieved to form the mastic. The coating that is achieved with the coarse and the fine fractions of the aggregate is dependent on the temperature of the water saturated bitumen when delivered to the spraying nozzles and the moisture regime that exists in the cold unheated damp aggregates (percentage of saturation of the material, normally between 65% and 85%). In practice, during the milling process when foamed bitumen is introduced, most old road bases are damp even in dry climates.

4.4.1 Temperature at the nozzles

A prerequisite of successful foamed bitumen stabilization is that a very small temperature differential should exist between the bitumen that is delivered to every nozzle. If this is not achieved streaking or uneven coating will occur. This is evidenced by the layout of the nozzles in the system patented by Salminen.

4.4.2 Pre-wetting of road surface before milling

It has been found that to dampen the road surface, prevents the picks of the milling machine to form dust, which in turn would limit the “balling” of the binder. This also allows more time for the suction forces to develop on the surface of the old base material, and it lessens the amount of water required for cooling the picks.

However, it must be stressed that if too much water is added during the milling or the degree of water saturation is too high, that this will lead to over saturation of the material especially the larger particles. Incomplete coating of these larger particles will occur because of the inadequate control of the moisture regime leading to a poor quality foamed bitumen layer.

4.4.3 Heat transfer

Another function of the heat of the water saturated bitumen is to heat the material to above ambient temperature. Following the “water phase” of the binder it adheres to the surface of the aggregate and on cooling it is “sucked” into the pores forming a bond between the damp material and water saturated bitumen.

This process of adsorption and absorption is thus enhanced by the suction forces developed during the milling and the mixing.

The level of material in the heat transfer area i.e. “boxed” above the milling drum and picks, must be accurately controlled as to prevent cold spots from forming in the material. The mixing action of the picks on the rotation drum of the recycling machine and the air insulation created by the movement of the material are of great importance. There must be material contact at all times between the outside cover and the picks on the drum, the moisture in the material will assist in cooling the picks (heat transfer). By setting this area correctly the optimum working temperature for the picks can be created improving pick life. This will differ from material type to material type and also to the level this material has been cemented or stabilized.

The amount of moisture to be absorbed during the water phase of the water saturated bitumen process are highly dependent on the effectiveness of the heat exchange during the mixing phase and the temperature of the reaction by which the water saturated bitumen is produced.

A simple hand test to verify the surplus water phase can be used to show the effective coating of the material to form the mastic. Adjustments can be made to the reactor water (foaming water) and the working temperature of the reactor for any given material.

Streaky mixing would be a clear sign of inadequate temperature control at the nozzles and in the “boxed” space above the milling drum.

5. REACTION PROCESS

This reaction is not a chemical but a physical chemical reaction.

5.1 The basic reaction

Cold water + hot bitumen = water saturated bitumen.

5.2 Description of the reaction

The reaction between the cold water and the bitumen can be described with the following example:

When water is placed on a red hotplate, it forms a drop of water that moves with a cracking and hissing sound. The molecules in the drop of water are excited to break through the surface tension of the water to form steam and eventually the evaporation causes the drop of water to cool down. This reaction on the hotplate will carry on until all the water has evaporated or when the place is to cold to sustain reaction through heat exchange. Throughout this process the drop of water is visible. This reaction is thus very basic and is only dependent on the amount of cold water used and the temperature the reaction has started from. It must be stressed that the water started with, ends up as water but in a super heated form.

By controlling the amount of water to be added, and by starting at the correct (optimum) temperature (see Appendix A for the correct temperature for the amount of water to be added). All the water can be bonded covalently into the bitumen. Water in this form bonds readily with hot bitumen. If this reaction takes place inside a reactor (pressure vessel) very little or no steam would be produced.

This reaction has two phases:

C Dispersion of the droplets of water in the bitumen that can be described as foaming.

C Approximately 25 seconds later (so-called half-life) the water droplets are covalently bonded into the bitumen to form a very stable water saturated bitumen. (See Appendix A).

It is at this point of the reaction that the Nesotec process and the modified Mobil process differs. Lewis et al(3) would sometimes add additives to the bitumen and to the water to form foam resulting the process to remain more or less in the dispersion phase (40% to 60% water saturated bitumen is formed).

In the Nesotec process, through carefully controlling the temperature and the amount of water added, no unreacted bitumen or free unbound cold water one is left in the reactor. Because this reaction takes place inside the reactor (pressure vessel) the water would remain in the droplet form to react readily with the hot bitumen to form water saturated bitumen. In this fully reacted phase 85% to 95% water saturated bitumen is formed that will react with the recycled fine aggregate to form a “mastic” resulting in a higher quality matrix of the recycled material.

6. **MIX DESIGN**

For mixed design purposes the SABITA MANUAL 14 for GEMS is followed using CBR, ITS and 3D dynamic testing (K-Mould) at 100% of MOD. AASHTO. The total fluid content is very close to the dry side of OMC, if the binder is deducted from total fluid content the amount of water required will be between 65% and 85% of the saturation requirement of the material.

The quality of foaming water is normally between 1.5% to 2.0% of the Binder and the Coefficient of foaming (Expansion Ratio) is taken at 25 seconds (half-live) and is a pure function of the selected working temperature. (The expansion ratio is 20 times at 150 degrees with 2% foaming water). NO FOAMING TAKES PLACE IF THE BINDERS TEMPERATURE DROPS BELOW 120°C. The binders temperature must be kept between 140°C (minimum) and 180°C (maximum). For every 1% of foaming water added the temperature will drop with 12°C.

Because of the differences between the two process (amount of water saturated bitumen that is manufactured) the Mobil Laboratory Reactor can only give an indication of percentage binder that is required for the CMI RS 500B/650 stabilizer with the Nesotec reactor. The true binder content must be established with a site trial section. The degree of weathering (% of water absorption) and the surface area of the material, determine the amount binder that is required for stabilization. This value is generally between 1.8% and 2.5% for a wide range of materials. This approach is also followed in Norway, these lower binder contents require higher expansion ratios (40 times),and this can be achieved if the hot bitumen is applied at 170 to 180 centigrade and the quantity of water that is added is about 1 to 1.5 percent

The percentage of 0.075mm in the material plays a major role in the stabilization process. The percentage water saturated bitumen that is being produced when the bitumen is foamed may require that this fraction be reduced to improve the material for early trafficking (to make the material more stable).

6.1 Typical field results

See Table 1

Table 1

Typical results with lockable platens at 25 degrees C

	ITS			UCS			K-Mould			CBR (derived from DCP	SPECIFICATIONS
Test Directions	Vertical			Horizontal			Horizontal			Horizontal	
Test Conditions	Unconfined			Unconfined			Partially confined			Totally confined	
Shear Plane	Indirect			3D in Shear			3D in Shear			3D in Shear	
Relative Relationships	UCS / 10 = ITS			CBR x 10 = UCS 1:1 = UCS 1:1 K-M			Esec. = CBR x 10 Esec. = UCS 1:1 K-M			UCS / 10 = CBR K-Mould/10 = CBR	A very strong Log relationship exists
Steynsrus - Lindley	Dolerite			with 1% OPC			and 2% Binder				48h at 60C
Cured for 48h@60C	138kPa (wet) 120kPa (dry)			1220kPa (wet) 1111kPa (dry)						160% 84% uncured	Min 140% cured Min 80% uncured
Estimated Emod.	Emod = 458 MPa (wet) Emod = 422 MPa (dry)			Esec = 1220 MPa (wet) Esec = 1111MPa (dry)			Est. Esec = 1220 to 1600 MPa (wet)			Esec = 1600 MPa	Min Esec = 1000MPa
Bothaville-Vaalriver	Rand Quartzite			+ Red Sand			and 2% OPC			and 2.1% Binder	Normally 1.8%-2.5%
Cured at 60 C for	24h	48h	72hr	24h	48h	72h	24h	48h	72h	72h	24h at 60C

			176(d) 73 (w)	1696 (d)	1518(d)	1282(d)	Esec = 1197 Gsec = 595 Ksec = 396	Esec = 6017 Gsec = 2315 Ksec = 645	Esec = 806 Gsec = 408 Ksec = 258	100%	(Dynamic Creep = 42 to 30 MPa) [24h c =7 and phi=86 deg 48h c =6 and phi=86 deg 72h c = 3.5 and phi=87 deg]
Estimated Emod. MPa			538 (d) 321 (w)	1696	1518	1282	1197	6017	806	1000	
Est. Life 10,000 (N 80kN axles 20,000 *x10^6) 30,000 load cycles							* 49.9 * 45.3 * 47.3	* 46.4 * 22.7 * 56.5	* 68.6 * 55.3 * 43.3		Life is based on a 200mm layer at Sig - 1=800kPa, a wheel track of 1M and at 10mm rut

6.2 **Curing Time**

The K-Mould and UCS tests were used to investigate the effect that curing time and drying had on the samples. In the test results the highest results were obtained with the 24 hour cured UCS's, the hysteresis curves for the 48 hours curing also showed signs of over curing. The sudden drop in stiffness in the 72 hour cured Esec from 1197 Mpa (24 hours) to 806 MPa clearly support this.

The water saturated bitumen has a water phase that is firstly adsorbed and then absorbed into the aggregate, if prolonged curing is used this mechanism is destroyed. In normal field conditions results very similar to the 24 hour test results would be produced. The strength of this material lies in the absorbed water bonded in the bitumen and thus onto the aggregate, with a higher concentration bonded onto the fines than onto the coarse aggregate. The coarse aggregate would during mixing be evenly coated with fines, the so called "mastic" after Salminen et al(6).

The typical results that is being produced by the 24 hour curing reflect the material characteristics of this material after stabilization. The very high Estimated Life N of 47,3 x 10^6 80kN axle load repitition (for a 10mm rut to form in a 200mm layer) reflect the very low level of deformation that can be expected (see Appendix C1 - C4). However, until the material has cured, it is sensitive to rutting. Great care must be taken in the design to prevent this.

7. PROPOSED MECHANISM OF THE FOAM/WATER SATURATED BITUMEN

The proposed mechanism of foaming or water saturated bitumen is schematically shown in Appendix B1. An approach is followed were by the first basic principles of the reaction are given in a simplified way, showing the basic concepts necessary to understand the process for normal use. It must be stressed that this process is a very dangerous explosive reaction that takes place at very high temperatures so please do not play around with this reaction. All that you need to know is already given (see Appendix A).

8. PROPOSED MECHANISM OF THE COATING PROCESS

The first basic principals are given schematically (see Appendix B2), showing the relationship between adsorption and absorption. The schematic reaction on the surface of the aggregate. The process of impregnation of weathered aggregate; this is the process that gives shelf life to foamed product. Process control can be done offsite because of this mechanism (only if no cement is added during the foaming). The two different coating systems of water saturated bitumen and foamed bitumen are given schematically.

9. APPLICATIONS IN PAVEMENT REHABILITATION

This is still a relative new pavement rehabilitation technique in South Africa. Before this new technique can be established for general use the basics must be solved. This is a fast track rehabilitation technique with a wide range of stabilizers that can be used with it, for doing deep in place cold recycling. The normal production rate is in the order of 9m/minute (2.6m wide) to full a cut depth of up to 450mm per production run (single cut). If however, the section is being rebuild under traffic the foaming option becomes attractive because the reworked section can be trafficked immediately so the need for a bypass falls away.

The in-situ materials can be utilized, borderline and weak material can improved, so this technique lends it self to pavement upgrade and deep rehabilitation.

Costs: Small projects smaller than 500m^2 = \$10 to \$12 per m^2

Larger projects larger than 8000m^2 = \$10 to \$4 per m^2

The following projects have been recycled by Raubex Road Recycling Division.

See Table 2.

Table 2

Raubex Construction: Road Recycling Division

NAME OF PROJECT AND BRIEF DESCRIPTION	CLIENT	CONSULTANT	COMMENCE-MENT DATE	COMPLE-TION DATE	VALUE IN RAND	DESIGN
Rehabilitation of Zastron Street in Bloemfontein	Municipality of Bloemfontein Mr C Bezuidenhout Tel. 051 405 8911	V3 Consulting Eng Mr G Verwey Tel. 051 447 7036	05/97	08/97	R 1 864 168.00	1% OPC 2% Bitumen
Repair of Breyten - Carolina Railway line	Protekon Mr J H Beukes Tel. 011 773 7164	Protekon Mr H Grabe Tel. 011 773 7164	07/97	09/97	R 520 000.00	1% OPC 3,5% Bitumen
Rehabilitation of Northern Access Pass, Katze Dam, Lesotho (Subcontract)	Lesotho Highlands Development Authority Mr I Sello Tel. 09266 31 1280	Lesotho Highlands Consultants Mr R Hagen Tel. 09266 96 0377	03/98	05/98	R 750 000.00	3% Bitumen
Rehabilitation of Andries Pretorius Str, Bloemfontein by deep milling method	Bloemfontein Municipality Mr C Bezuidenhout Tel. 051 405 8911	V3 Consulting Eng Mr G Verwey Tel. 051 447 7036	06/98	07/98	R 1 591 067.00	1% OPC 2% Bitumen
Repair of sections of N5 between Winburg and Harrismith and Steynsrus - Lindley - Bethlehem Road	Free State Government Mr K Arnold Tel. 051 405 4188	VKE Mr Ivan Jacobs Tel. 051 447 9816	11/97	03/98	R 9 360 405.00	Varied
Rehabilitation of R102 Tongaat	North Local Council	Vija Ori & Ass De Leuw Cather Joint Venture - Mr V K Ori Tel. 0332 92000	02/98	10/98	R 4 570 000.00	1% OPC 1,8% Bitumen
Bothaville - Vaal River Road Rehabilitation (Subcontract)	Free State Government Mr K Arnold Tel. 051 405 4188		09/98	06/99	R10 700 000.00	2% OPC 2,1% Bitumen

10. CONCLUSIONS

During the past eighteen months valuable hands-on experience have been gained in the field use of water saturated bitumen, which lead to the solving of the following:

Mechanism of foam/water saturated bitumen

Mechanism of the coating process

Mix Design using 100% of Mod. AASHTO compaction techniques

The relative relationship between the basic tests

The use of dynamic 3D testing to predict, the Esec -, Gsec -, Ksec values, N life, phase angle, Volumetric Esec values, Fractional dilation and Permanent dilation of a given material

Development of materials specifications

More development and research is still required to include a wider range of materials

11. ACKNOWLEDGEMENTS

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4. Van der Walt N., GIBB Africa, Lewis T., AA L oudon& Partners, Botha P., Technical Specialist. **The use of foamed bitumen in the rehabilitation of pavement layers**. Durban, 14 October 1993. **4th International conference on Managing Pavements.**

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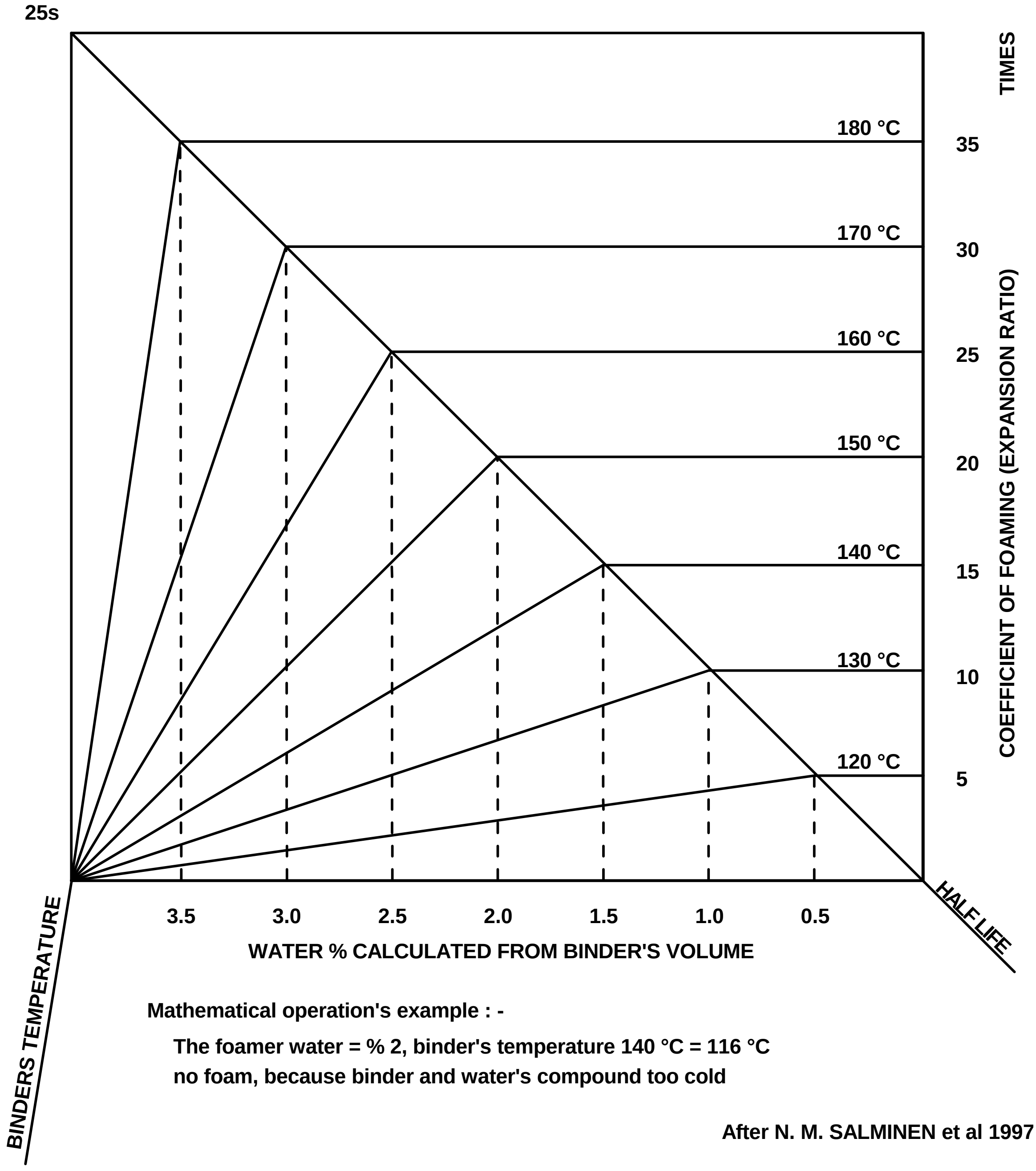
months.

6. SABITA Manual 14, October 1993. **Gems the design and use of granular emulsion mixes.**

CMI RS-500B/650/ CAT BR - 250 STABLIZATION

- **half life time is always 25 seconds**
- **binder's temperature min 140°C and max 180°C**

Note :- **1 % water reduce binder's temperature 12°C downward, no foaming takes place below 120°C**



Mathematical operation's example : -

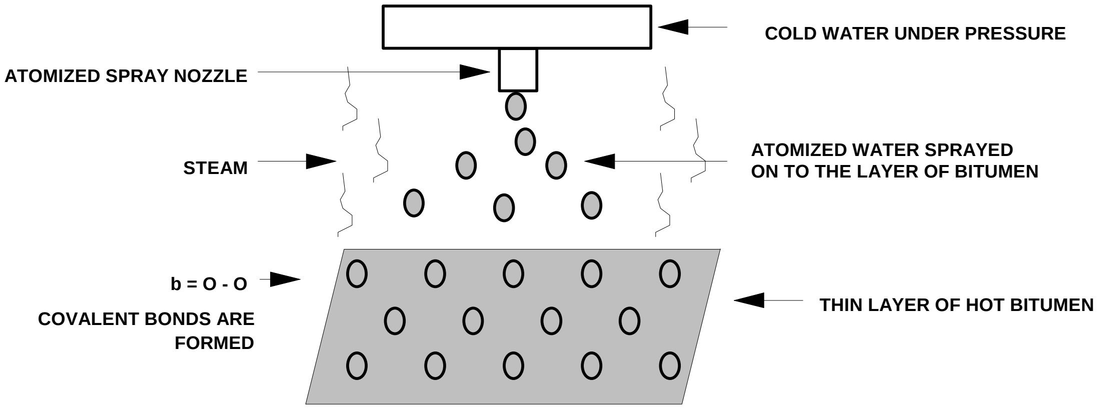
The foamer water = % 2, binder's temperature 140 °C = 116 °C
no foam, because binder and water's compound too cold

After N. M. SALMINEN et al 1997

APPENDIX A

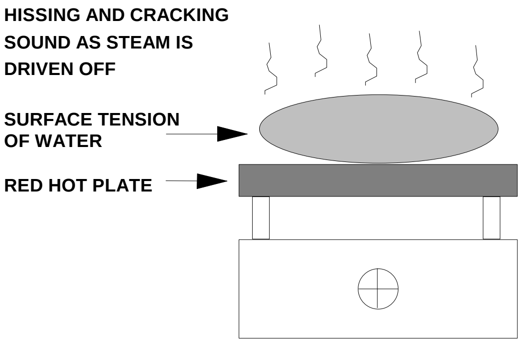
BITUMEN3.DRW

PROPOSED MECHANISM OF FOAM / WATER SATURATED BITUMEN

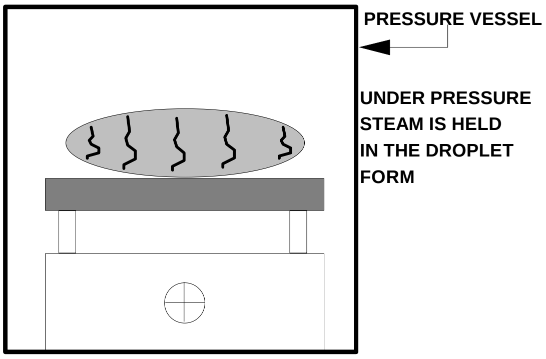


(WATER SATURATED BITUMEN IS FORMED AFTER 25 SECONDS)

SUPER HEATED WATER



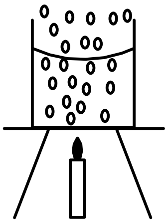
SUPER HEATED WATER IN A PRESSURE VESSEL



THE FOLLOWING EXAMPLES HIGHLIGHTS THE MAIN DIFFERENCES BETWEEN THE NESOTIC AND THE MOBIL SYSTEM

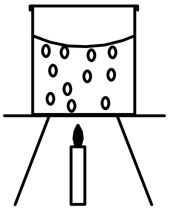
FOAMED BITUMEN

WATER IN BOILING OIL, BITUMEN IS ENERGIZED AND THE VISCOSITY IS LOWERED.



WATER SATURED BITUMEN

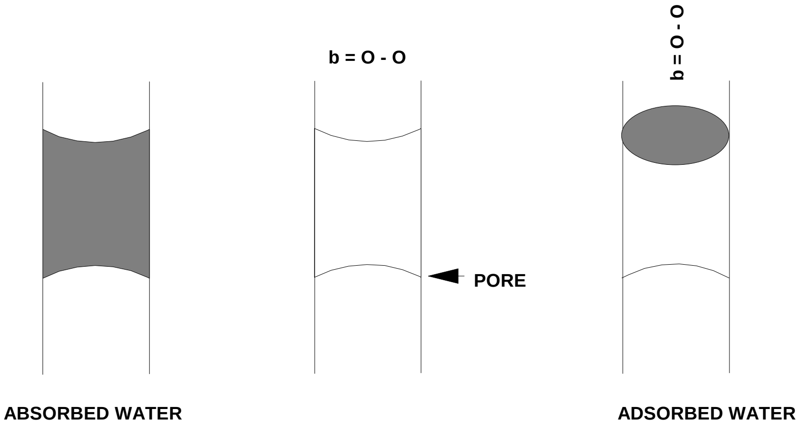
WATER IN HOT OIL, SIMULATING WATER SATURATED BITUMEN (VOLUME IS INCREASED AND VISCOSITY IS LOWERED.)



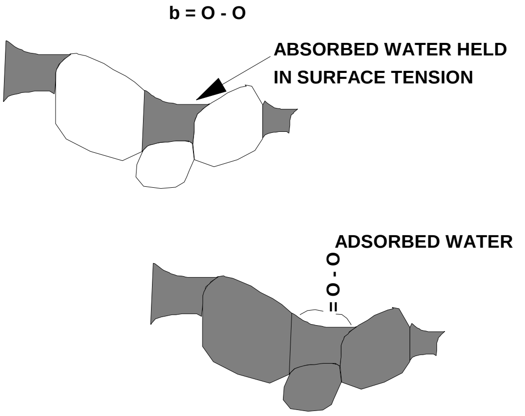
BITUMEN1.DRW

APPENDIX B1

PROPOSED MECHANISM OF THE COATING PROCESS
THE BASIC RELATION OF ADSORPTION / ABSORPTION IN PORES

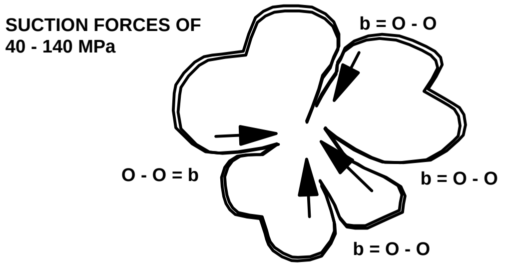


SURFACE ADSORPTION



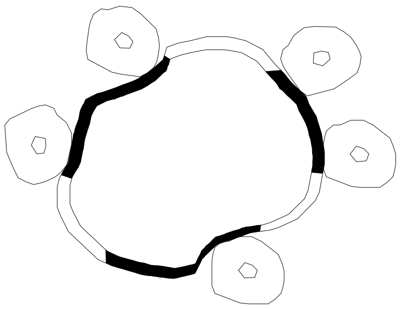
IMPREGNATION

COVALENT BOND REQUIRE 520 °C
TO DESTROY THIS BOND



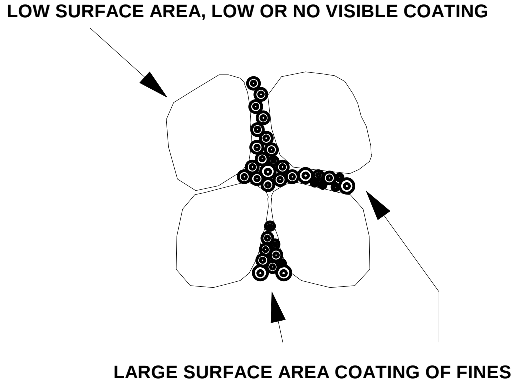
IMPREGNATION IS TIME DEPENDENT (HEAT EXCHANGE
/ SUCTION FORCES - OSMOSES/ DIFFISION)

WSB COATING OF MATERIAL



HOMOGENIOUS COATING

FOAM COATING OF MATERIAL



BITUMEN2.DRW

APPENDIX B2

```
FA117A- (FC=3.1%)(LOAD=6.5kN)(hav02)(98/10/15)(avg)
         789.8101 0.002632 0.082449                            1013.986 0.000548 0.123943
         129.2315 0.002080 0.572731                            356.3147 -0.00004 0.609154
Esec     1196.790                   0.143958 Damping factor    1115.347 Volumetric Esec   0.203467 Dilation damping
                                                                                           0.000017 Permanent dilation


         319.4812 0.002493 0.031370
         8.141871 0.001970 0.255948
Gsec     594.8890                   0.122565 Damping factor

         337.9953 0.667542 0.010298
         117.7172 0.667356 0.064109
Ksec     396.2981                   0.160633 Damping factor

                                    0.142385 Damping factor (avg)

logEsec vs A (A=log(Theta/pa))                        logEsec vs A,B (B=log(Tau-oct/pa))
         Regression Output:                                    Regression Output:
Constant                  3.298423                    Constant                  1.597449
Std Err of Y Est          0.058350                    Std Err of Y Est          0.034435
R Squared                 0.229205                    R Squared                 0.743751
No. of Observations             24                    No. of Observations             24
Degrees of Freedom              22                    Degrees of Freedom              21

X Coefficient(s)  -0.23636                            X Coefficient(s)  2.011794 -1.02197
Std Err of Coef.  0.092410                            Std Err of Coef.  0.350476 0.157379

logEsec vs C,A,B (C=log(Sig1/Sig3))                   logEsec vs log(Theta)
         Regression Output:                                    Regression Output:
Constant                  2.316782                    Constant                  3.772552
Std Err of Y Est          0.033499                    Std Err of Y Est          0.058350
R Squared                 0.769043                    R Squared                 0.229205
No. of Observations             24                    No. of Observations             24
Degrees of Freedom              20                    Degrees of Freedom              22

X Coefficient(s)  4.552700 -1.86299 -2.44928          X Coefficient(s)  -0.23636
Std Err of Coef.  3.076281 2.640319 0.976516          Std Err of Coef.  0.092410

FA117A- (FC=3.1%)(LOAD=6.5kN)(hav02)(98/10/15)(avg)
Esec(MPa)(Smax)   1196.790          J1       1014.339          I1       0.002588          SD-kg/m^3              2650
Gsec (MPa)(Smax)  594.8890          J2       189938.5          I2        1.7E-07          FC(%)                   3.1
Ksec (MPa)(Smax)  396.2981          J3       9954224.          I3       2.60E-12          SD-min(kg/m^3)     1979.893
Sig-1(max)(kPa)   789.8101          J1'      663.0557          I1'      0.000445          SD-max(kg/m^3)     1981.060
Sig-1(min)(kPa)   129.2315          J2'      1637.934          I2'      6.18E-08          SD-min(%SD)        74.71295
Sig-3(max)(kPa)   112.2644          J3'      1013.432          I3'      1.57E-12          SD-max(%SD)        74.75701
Sig-3(min)(kPa)   111.0258          DampE    0.143958          c1(kPa)  -15.7066          Poisson-max        0.464656
Eps1max           0.002632          DampG    0.122565          Phi1(deg)88.81382          Poisson-min        0.127738
Eps1min           0.002080          DampK    0.160633          c2(kPa)  7.148361          Poisson-avg        0.299048
Eps3max           0.000031          Damp(avg)0.142385          Phi2(deg)85.87503
Eps3min          -0.00002

FA2MM - Foam-asphalt (24hr curing)
   Sig-1    Sig-3    Theta    START     5000    10000    20000    30000
   (kPa)    (kPa)    (kPa) Esec(MPa)Esec(MPa)Esec(MPa)Esec(MPa)Esec(MPa)
     200      112      424   1754.7    968.6   6697.1   1849.2    753.2
     300      112      524   1236.8   1180.4   1958.2    958.3    804.2
     400      112      624   1136.6   1223.2   1352.9    863.6    857.2
     500      112      724   1130.3   1209.5   1218.0    911.5    907.9
     600      112      824   1160.0   1174.9   1225.2   1020.5    955.9
     700      112      924   1207.2   1133.1   1299.3   1169.8   1001.3
     800      112     1024   1264.4   1089.6   1415.4   1352.1   1044.4
     900      112     1124   1327.5   1047.2   1563.1   1564.7   1085.5
    1000      112     1224   1394.7   1006.9   1737.7   1806.7   1124.7
```

APPENDIX C1

```
FA2MM - Foam-asphalt (24hr curing)

Def-200 (last 4 readings)(10000 reps)
         Regression Output:                             1m     0.6m
Constant                    0.140876          Sig1(avg)799.7338 799.7338
Std Err of Y Est            0.009246          Width    0.252355 0.420592
R Squared                   0.220878          Kmax       0.4013   0.3372
No. of Observations               16          Kmin       0.3974   0.3336
Degrees of Freedom                14          Fraction 0.098709 0.162802

X Coefficient(s)  0.000001
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```
Std Err of Coef.  0.000001

Permanent deformation          10mm     10mm      5mm      5mm
load repetitions(10mm)     4934610. 4934610. 2432050. 2432050.
Wheel track (Normal dist)        1m     0.6m       1m     0.6m

N                          49991399 30310477 24638537 14938686

Def-200 (last 4 readings)(20000 reps)
        Regression Output:                                 1m     0.6m
Constant                   0.161026          Sig1(avg)796.5851 796.5851
Std Err of Y Est           0.007631          Width    0.252853 0.421422
R Squared                  0.433853          Kmax       0.4013   0.3372
No. of Observations              20          Kmin       0.3974   0.3336
Degrees of Freedom               18          Fraction 0.098711 0.162805

X Coefficient(s)  0.000002
Std Err of Coef.  0.000000

Permanent deformation          10mm     10mm      5mm      5mm
load repetitions(10mm)     4475720. 4475720. 2201234. 2201234.
Wheel track (Normal dist)        1m     0.6m       1m     0.6m

N                          45341595 27491272 22299763 13520672

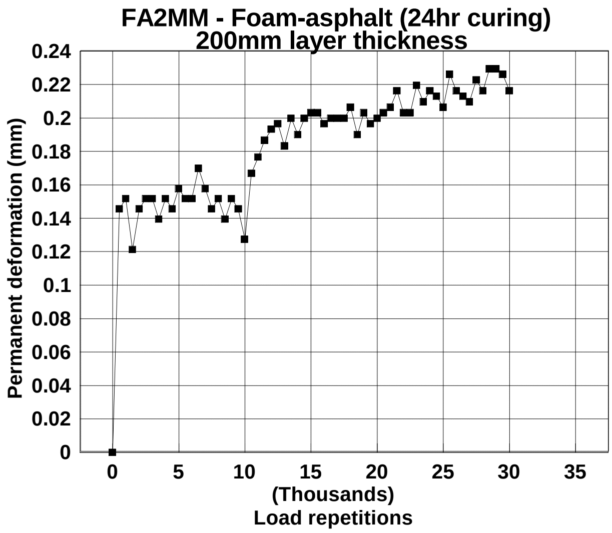
Def-200 (last 4 readings)(30000 reps)
        Regression Output:                                 1m     0.6m
Constant                   0.161785          Sig1(avg)796.8712 796.8712
Std Err of Y Est           0.006346          Width    0.252808 0.421346
R Squared                  0.527100          Kmax       0.4013   0.3372
No. of Observations              21          Kmin       0.3974   0.3336
Degrees of Freedom               19          Fraction 0.098710 0.162804

X Coefficient(s)  0.000002
Std Err of Coef.  0.000000

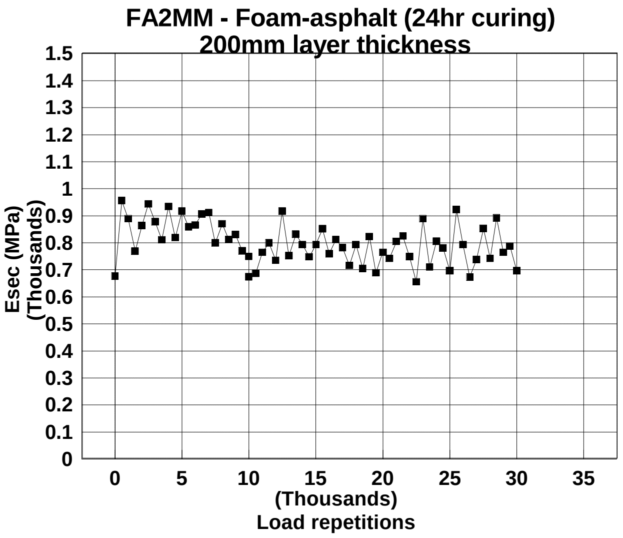
Permanent deformation          10mm     10mm      5mm      5mm
load repetitions(10mm)     4674009. 4674009. 2298573. 2298573.
Wheel track (Normal dist)        1m     0.6m       1m     0.6m

N                          47350464 28709276 23285903 14118582
```

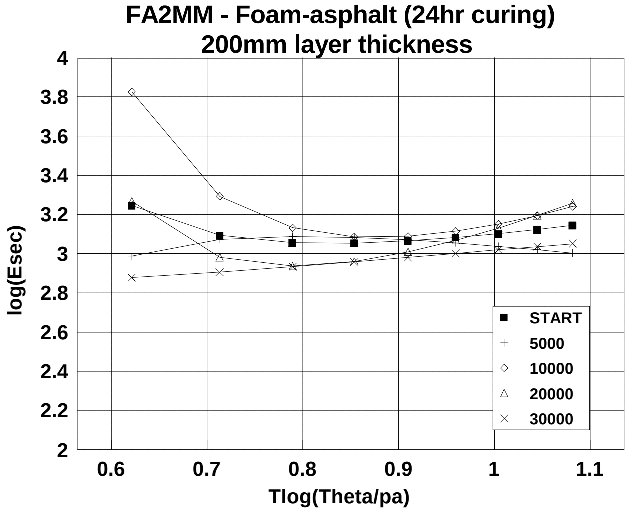
APPENDIX C2



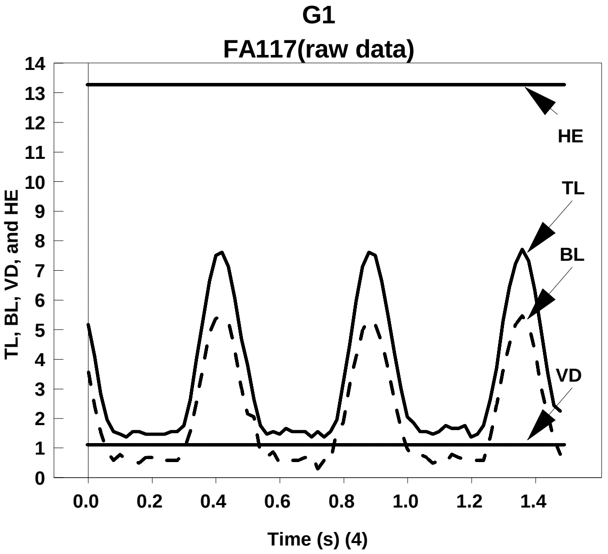
FA2MM - Foam-asphalt (24hr curing) 200mm layer thickness



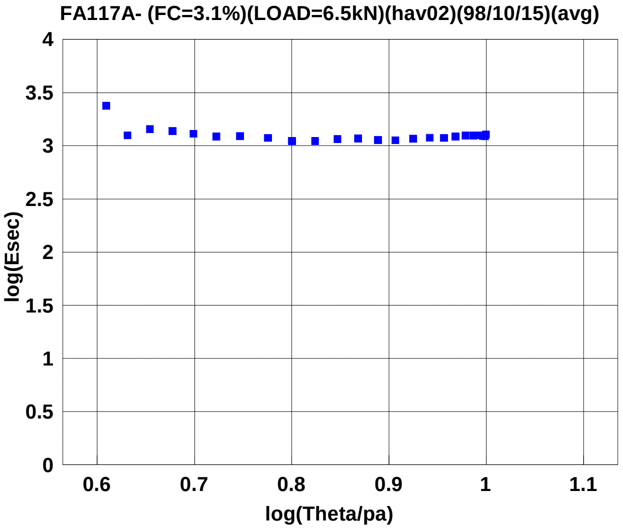
FA2MM - Foam-asphalt (24hr curing) 200mm layer thickness



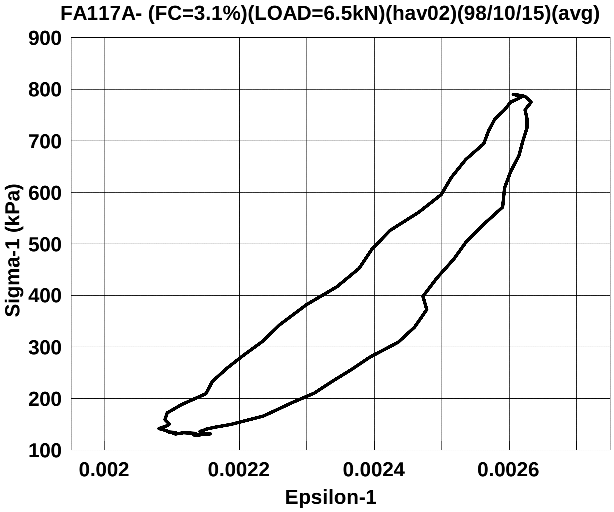
FA2MM - Foam-asphalt (24hr curing) 200mm layer thickness



G1
FA117(raw data)



FA117A- (FC=3.1%)(LOAD=6.5kN)(hav02)(98/10/15)(avg)

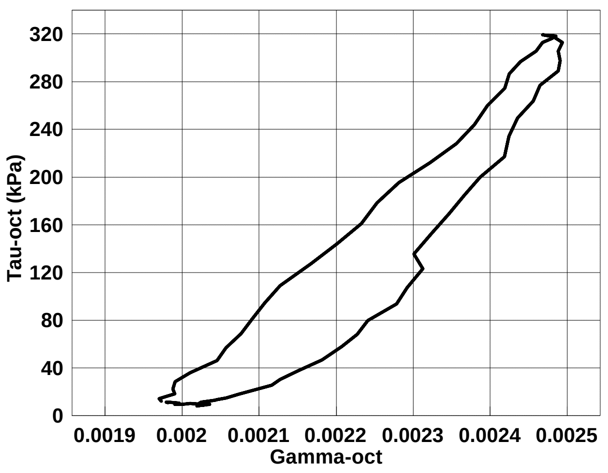


FA117A- (FC=3.1%)(LOAD=6.5kN)(hav02)(98/10/15)(avg)

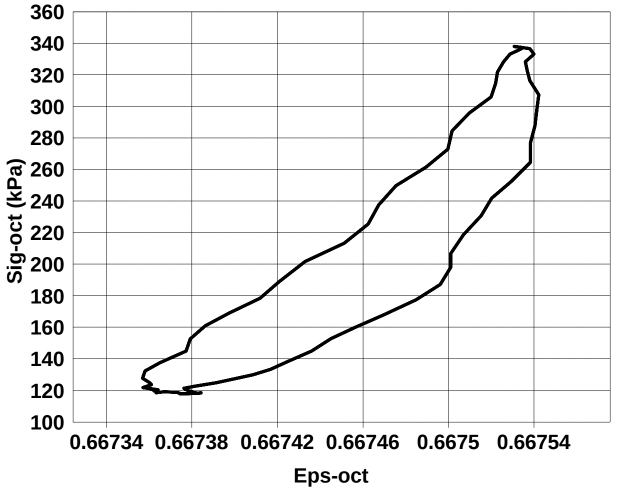
BITUMEN4.DRW

APPENDIX C3

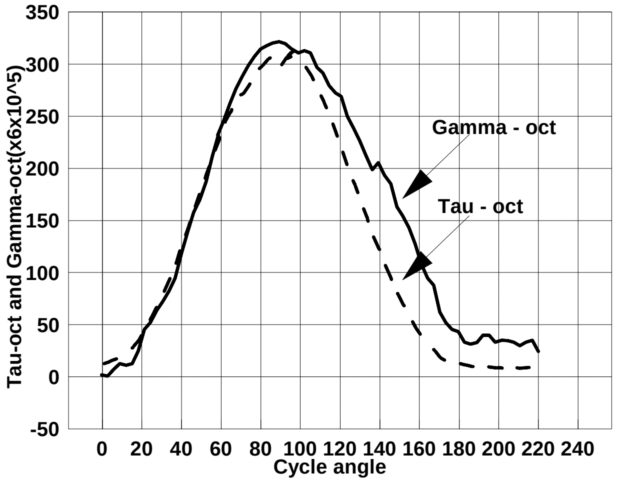
FA117A- (FC=3.1%)(LOAD=6.5kN)(hav02)(98/10/15)(avg)



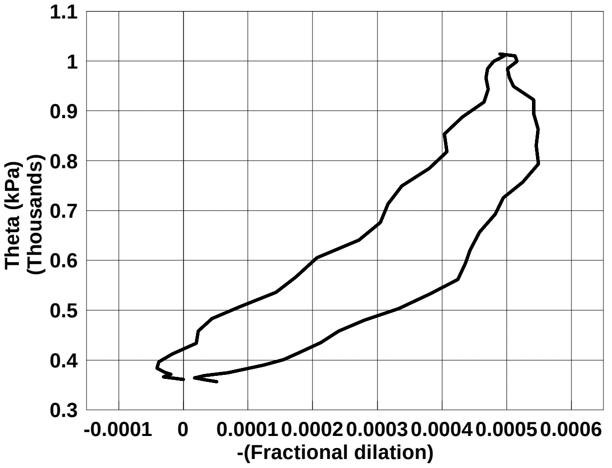
FA117A- (FC=3.1%)(LOAD=6.5kN)(hav02)(98/10/15)(avg)



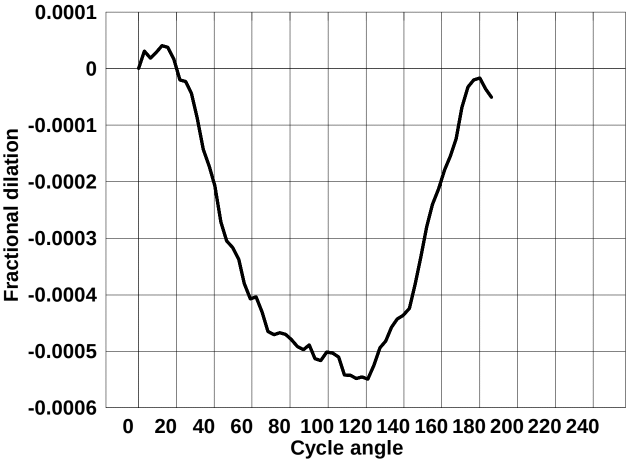
FA117A- (FC=3.1%)(LOAD=6.5kN)(hav02)(98/10/15)(avg)



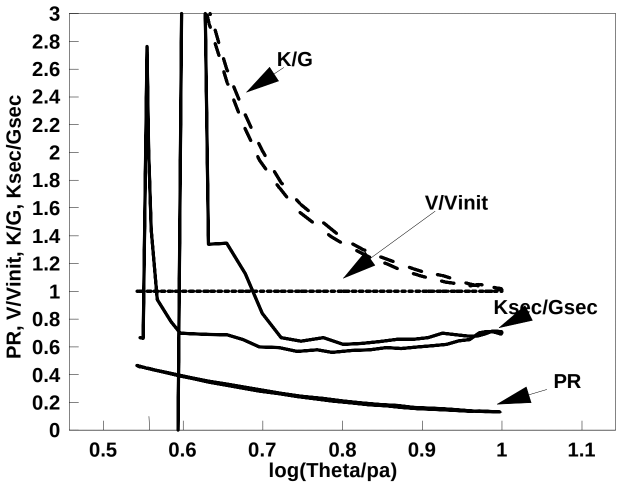
FA117A- (FC=3.1%)(LOAD=6.5kN)(hav02)(98/10/15)(avg)



FA117A- (FC=3.1%)(LOAD=6.5kN)(hav02)(98/10/15)(avg)



FA117A- (FC=3.1%)(LOAD=6.5kN)(hav02)(98/10/15)(avg)



BITUMEN5.DRW

APPENDIX C4