▸▸ Under the patronage of **H.E. Dr. Abdullah Belhaif Al Nuaimi** - Minister of Infrastructure Development

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Sustainable Flexible Pavement in Terms of Micro Crack Healing Concept

[Learning session 03]

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- Asphalt concrete mixture provides the necessary stiffness and strength properties through its aggregate skeleton and offers a damping ability through its visco-elastic asphalt binder. From the sustainability point of view, asphalt concrete production consume energy and produce emissions and requires the consumption of natural resources such as aggregates.

Problem statement

Asphalt mixtures suffer damages from many factors such as traffic load, temperature variations, and oxidations. The dominant mechanism of damage in asphalt mixtures at low temperature is microcrack formation, growth, and ultimately formation and propagation of macrocracks.

Fatigue is the result of a crack initiation process followed by a crack propagation process.

Such cracking exhibit a durability problem.

Fatigue is a two-stage process:

(1) Microcrack growth and healing.

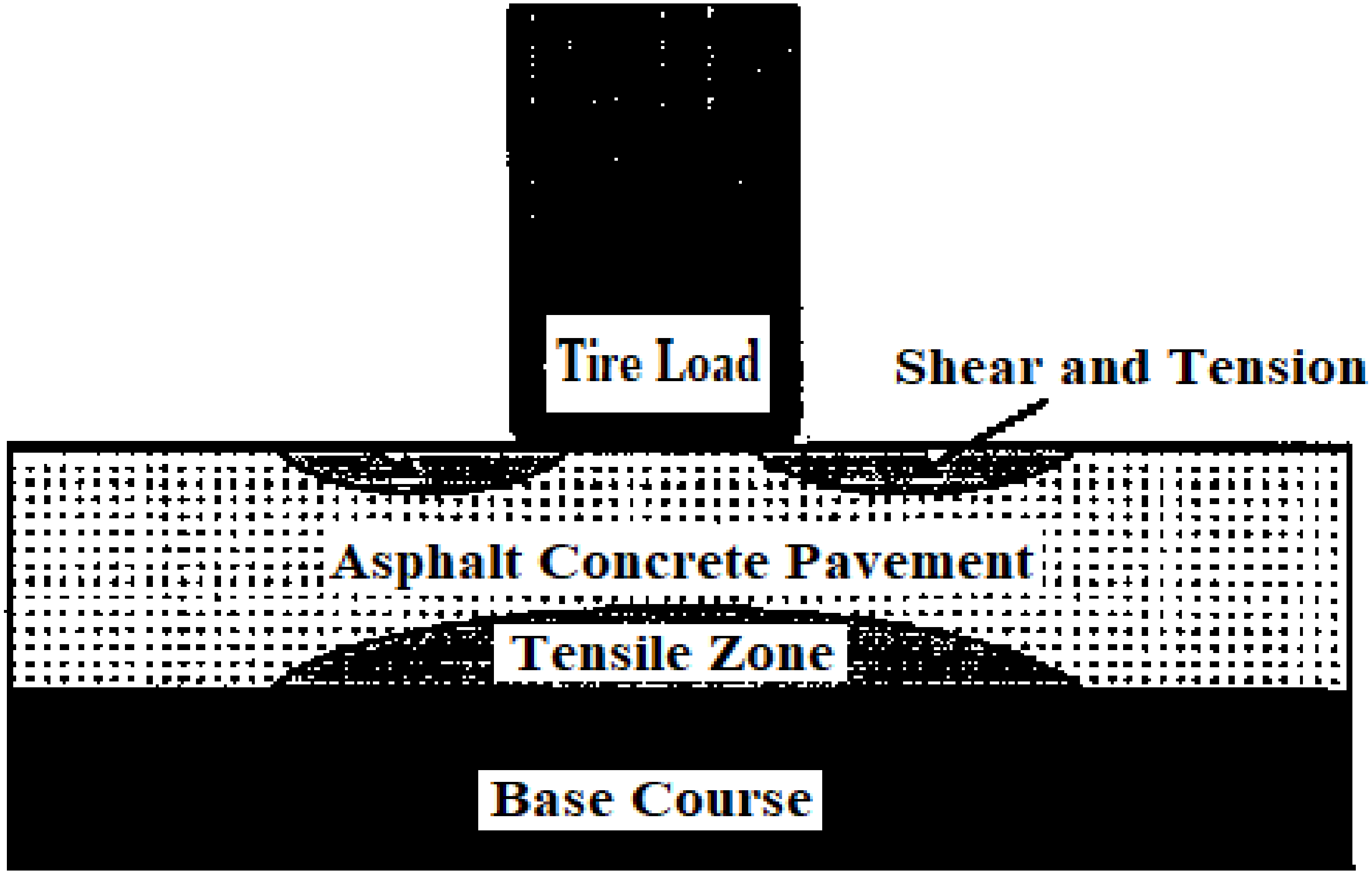
(2) Macrocrack growth and healing.

The two stages are governed by the same Paris' law.

Paris' law coefficients A and n are known to depend strictly upon more fundamental properties. The chief among them are the compliance and tensile strength (mechanical properties) and the adhesive and cohesive surface energy density (chemical and thermodynamic properties).

- **Both microcracks and macrocracks can be propagated by tensile or shear stresses or combinations of both. Microcracks form and grow in any location where sufficiently large tensile or shear stresses or a combination of both are generated by traffic or environmental stresses.**

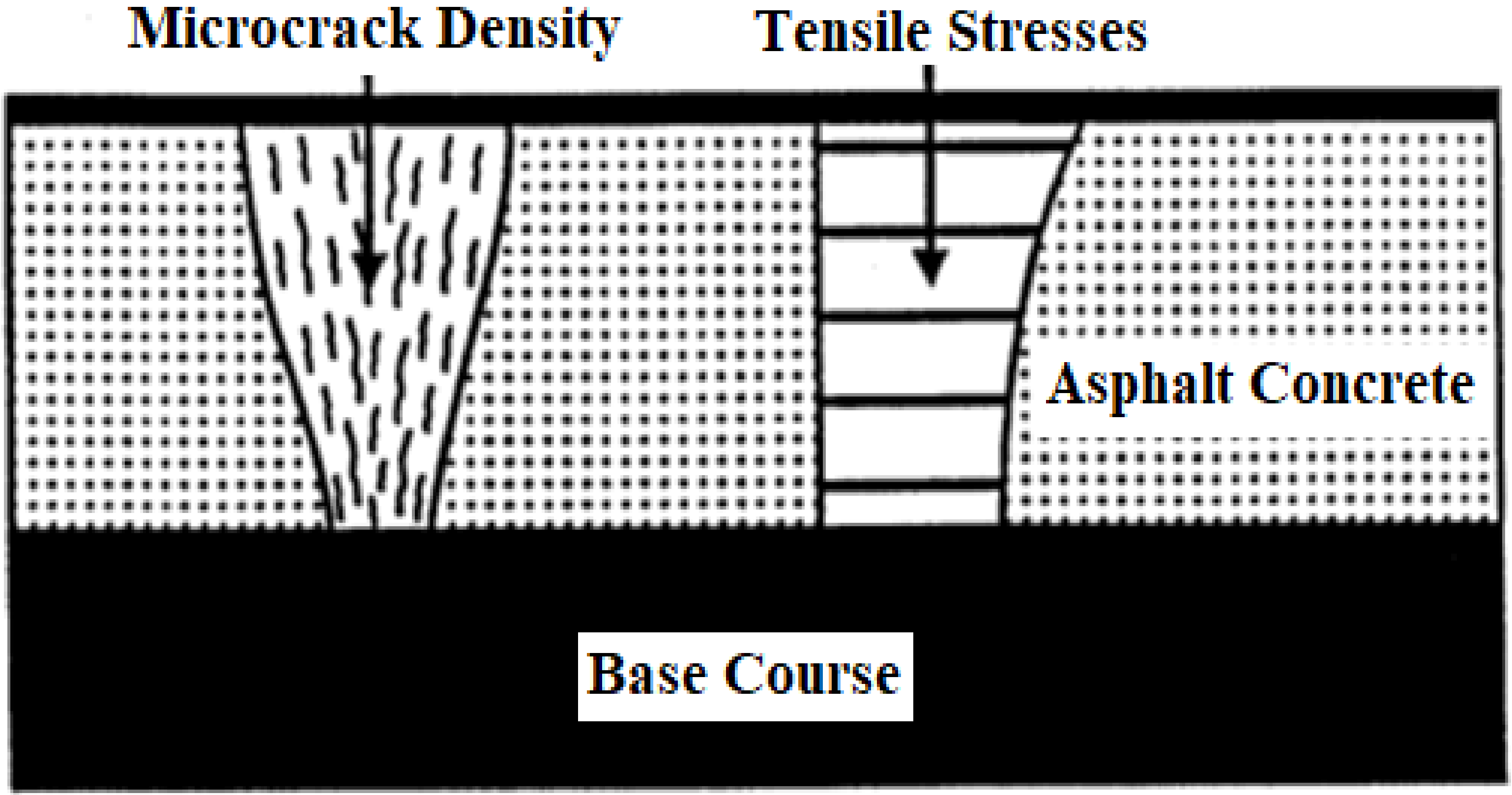
- **The locations of such zones relative to the placement of a tire are shown schematically in the following figure**



Tire Load
Shear and Tension
Asphalt Concrete Pavement
Tensile Zone
Base Course

Microcrack zones can be introduced into the pavement by thermal stresses due to a drop in the air temperature as shown schematically in the following Figure.

These cracks may grow, reach critical size, and propagate due to either a significant decrease in temperature or to smaller repeated daily deceases in temperature.


Microcrack Density
Tensile Stresses
Asphalt Concrete
Base Course

Fatigue usually initiates from the bottom of asphalt layer due to the accumulation of damage occurred in the layer under repeated load application. The maximum tensile strain at the bottom of asphalt concrete layer is generally used to indicate the rate of fatigue cracking for tradition flexible pavement. After some years of service, the stiffness of asphalt concrete mixture increases, and its elastic properties decreases, the asphalt binder becomes more brittle and micro-cracks develop in it and cracking of the interface between aggregates and binder occurs.

Another type of cracks is the top-down cracking which is a deterioration mechanism that has been identified in temperate- climate countries. However, it is far from being completely controlled. Its causes are still not sufficiently known. Climatic conditions, traffic, ageing, structure and construction quality is the main causes pointed out for the initiation and propagation of such type.

- **Cracks are initiating at the surface and at the bottom of the asphalt concrete layer.**

Surface initiation is more common in thick asphalt layers (>200 mm).

Bottom initiation is more common in intermediate thickness layers (50-200 mm).

Micro Cracks Healing of Asphalt Concrete

Healing can be observed both in the cohesive and adhesive regions of asphalt mixtures. Healing is considered to be cohesive when occurring in the asphalt or mastic and to be adhesive when occurring at the asphalt-aggregate interface.

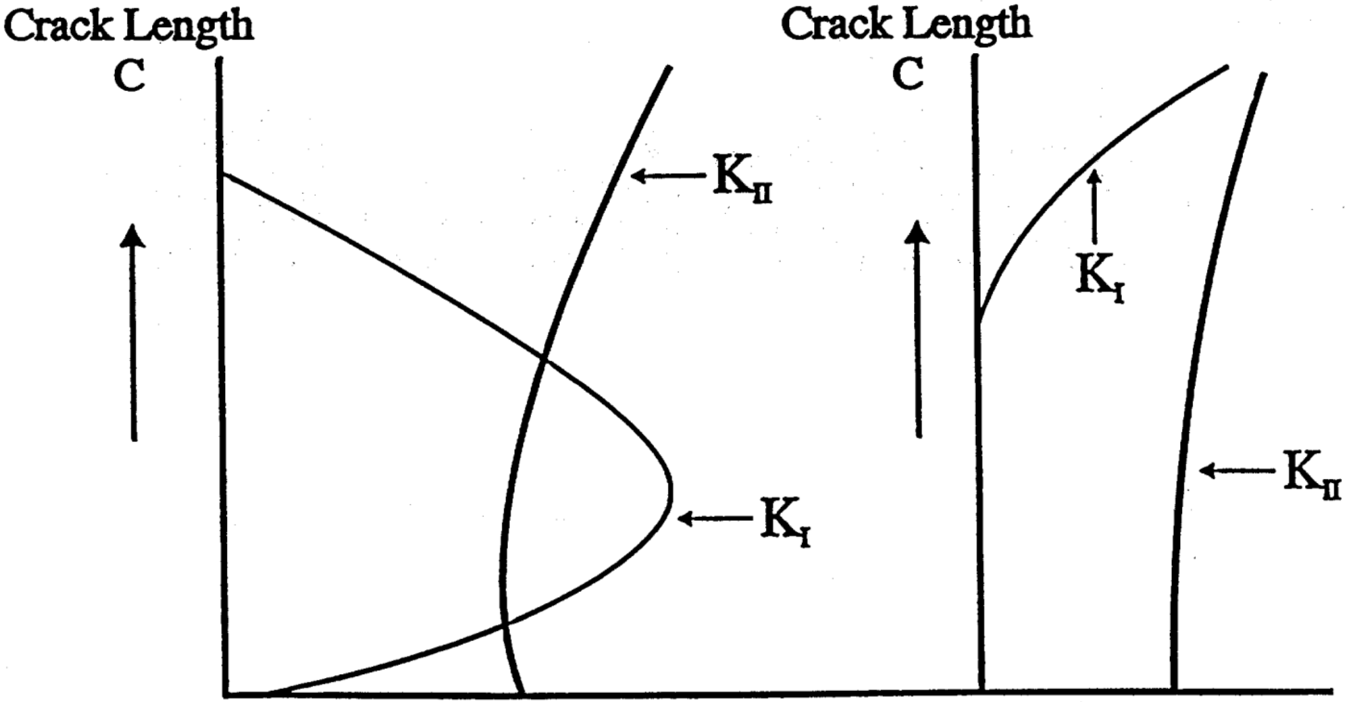
Adhesive healing at the asphalt – aggregate interface is due to the re bonding of the asphalt to the aggregate; and cohesive healing within the asphalt binder is due to the cross-linking of asphalt materials at the micro crack surface.

The number of traffic load cycles, N_f to cause a crack to penetrate through the full depth of the pavement surface layer is the sum of the number of load cycles for crack initiation, N_i and the number of load cycles required for the macrocrack to propagate to the surface, N_p .

$$N_f = N_i + N_p$$

Paris' law states that the "crack speed," dc/dN depends upon the size of the elastic equivalent, the stress intensity factors due to tension (K1 and shear Kn). The distribution of K1, and Kn, varies with depth.

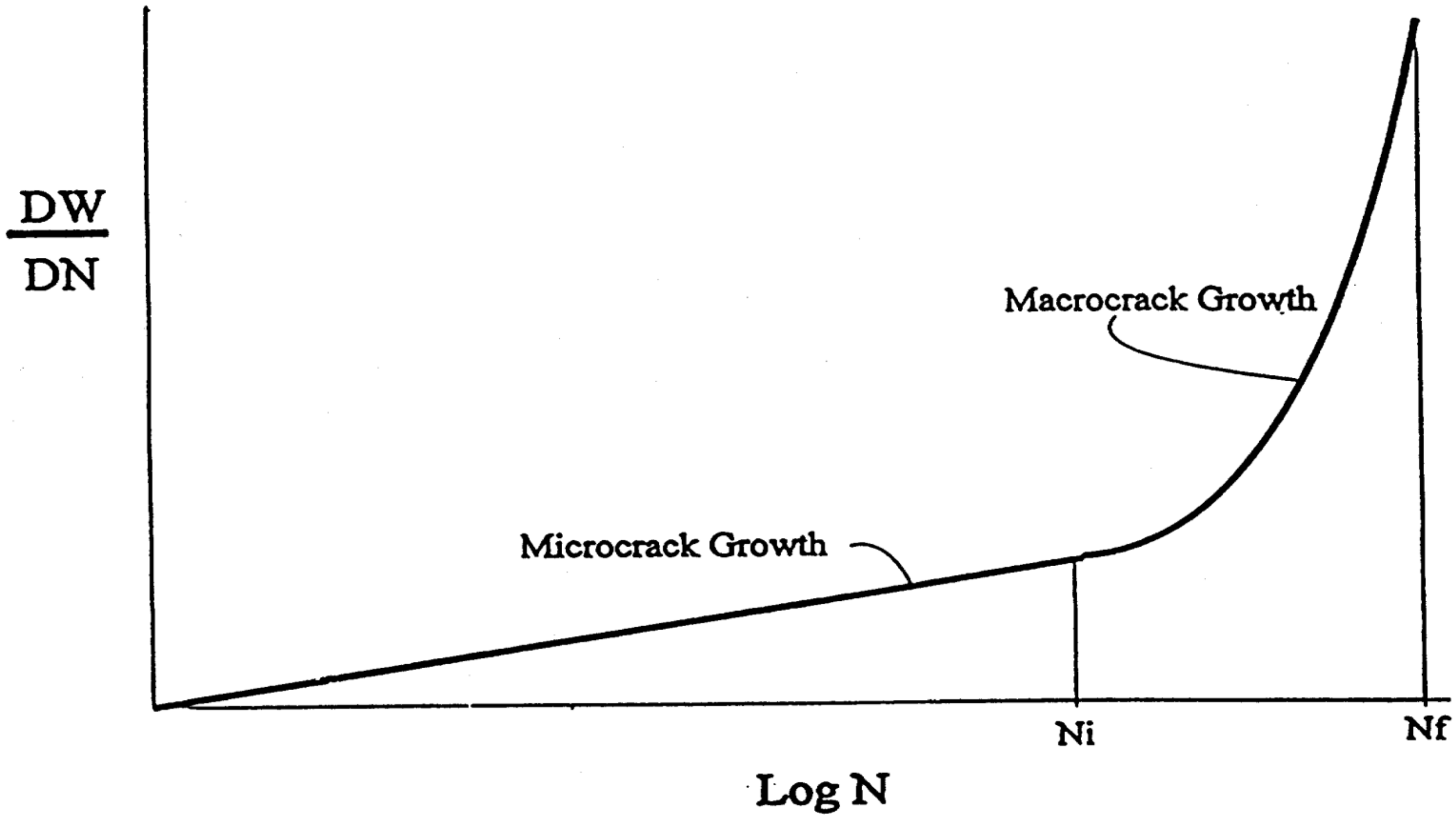
Both Ni and N_p obey Paris' law and modified to include both fracture and healing. The actual number of load cycles required in each process is calculated by the following figure.



Crack Initiating at the Bottom

Crack Initiating at Surface

Not only does the stress-intensity factor change with crack length, but the values of the Paris' law coefficients A and n for both fracture and healing also vary depending upon whether the crack is momentarily growing along the surface of an aggregate (adhesive fracture) or in the mastic surrounding the aggregate (cohesive fracture), or temporarily arrested by an object blocking its path (crack arrest).


DW
DN
Macrocrack Growth
Microcrack Growth
Ni
Nf
Log N

- **The fatigue life of asphalt pavements can be extended by the crack closer and retardation of additional crack growth through healing effect.**

Microcrack Healing theories

Three-step diffusion model was proposed to explain the healing of bitumen, closing of cracks due to wetting (adhesion of two crack surfaces together driven by surface energy), closing of cracks due to consolidating stresses and asphalt flow, and the complete recovery of mechanical properties due to diffusion of Asphaltenes structures.

- The healing of asphalt mixes during rest periods by the sol–gel theory

At high temperature, healing happens due to the transition from sol to gel of bitumen and, if the rest period is enough, damage recovery will be complete.

At low temperature, rest periods do not allow the healing of structural damage created by the loading cycles and recovery would only be partial.

Finally, it is well known that healing of asphalt concrete is a temperature dependent phenomenon.

Healing in asphalt mixtures is a two-step process, this model represents healing as a convolution of wetting and intrinsic healing processes that occur across a crack interface. The process of the cracked surfaces coming into contact with each other is referred to as wetting. The rate of wetting is influenced by the mechanical properties of the material as well its surface free energy. The strength gained by a wetted crack interface over time is referred to as intrinsic healing and can be defined as the ratio of a mechanical property of interest, for the volume enclosing the crack at unite time, to the mechanical property of the intact material without damage.

Factors Influence Micro Cracks Healing

1- Impact of material properties:

A relationship between the crack closing speed and material properties such as the work of cohesion and compliance parameters was developed. The rate of self-healing in asphalt mixtures depends on the type of asphalt binder and properties of the mixture. It is desirable to select materials that maximize the self-healing capabilities of the mixture.

2- Influence of Volumetric Properties

- For an asphalt mixture, a high healing potential is found to be related to high bitumen content. In addition, healing also increases with an increase of the voids filled with bitumen, a decrease of the voids in mineral aggregate skeleton and a decrease of the volume of air void.

3- Influence of Physical property and Chemical Composition of Asphalt Cement

-**Soft bitumen** with a higher penetration grade and a lower softening point has a higher healing capability than hard bitumen.

-Bitumen's with **low amphoteric and high aromatic** contents were found to be better healers. In addition, the heteroatom content promotes healing because sulfur, oxygen and nitrogen promote the polarity of bitumen.

4- Influence of asphalt Modifiers

Modified binder shows a better healing potential than the base asphalt. The modification techniques can alter the healing performance. The healing of asphalt mixtures with different modifications like Styrene Butadiene Styrene (SBS), Styrene Butadiene Rubber (SBR) and Gilsonite (GIL) have been compared. Asphalt mix with the SBS modifier showed the best performance with regard to fatigue, rutting and healing. The healing rate of polymer modified binders is significantly better than that of the neat binders. Addition of hydrated lime can significantly improve the healing capability.

5- Effect of Ageing

- A negative effect of ageing on the healing capability of a laboratory aged specimen was reported.
- Laboratory aged mortar shows a higher healing capability compared to the virgin mortar.
- Field aged mortar, which had the same rheological and chemical properties as the laboratory aged mortar, shows a lower healing capability compared to the virgin mortar.
- At mixture level, laboratory simulated aging slightly decreases the healing capability of a porous asphalt mixture

6- Inclusion of Temperature

- Temperature could be applied either by induction heating or as external heating. The self-healing capability is related to the viscosity of the bitumen, which increases with increasing healing time, temperature and when the crack size is very small.
- The healing recovery of asphalt concrete depends on the capillary flow of bitumen through the crack.
- The most appropriate way for healing asphalt concrete is to increase the temperature above the Newtonian transition (50ºC) and maintain it for a certain amount of time.

- A secondary benefit of subjecting asphalt mixtures to elevated temperatures after certain periods of time is that steric hardening within the asphalt binder is reversed. Therefore, application of thermo-mechanical treatment at periodic intervals can result in reversal or fatigue crack growth and extension of pavement life.
- Addition of conductive fibers and fillers, improve the conductivity, and heating with induction energy can increase its self-healing rate.

7- Influence of Surface Free Energy

-The difference between the total fracture and healing surface energies lies in the measurement of the individual surface energy components using carefully selected materials with known surface energy component values.

-Healing depends on the surface energy of the material (wetting, to put both faces of the crack in complete contact) and on the inter diffusion and randomization capacity of the molecules from one face to the other.

-surface free energy can be divided into two parts being the Lifshitz-Van der Waals component which has a negative effect on the short term healing, and the Lewis acid-base component, which shows a positive effect on the long term healing.

8- Inclusion of Rest Periods

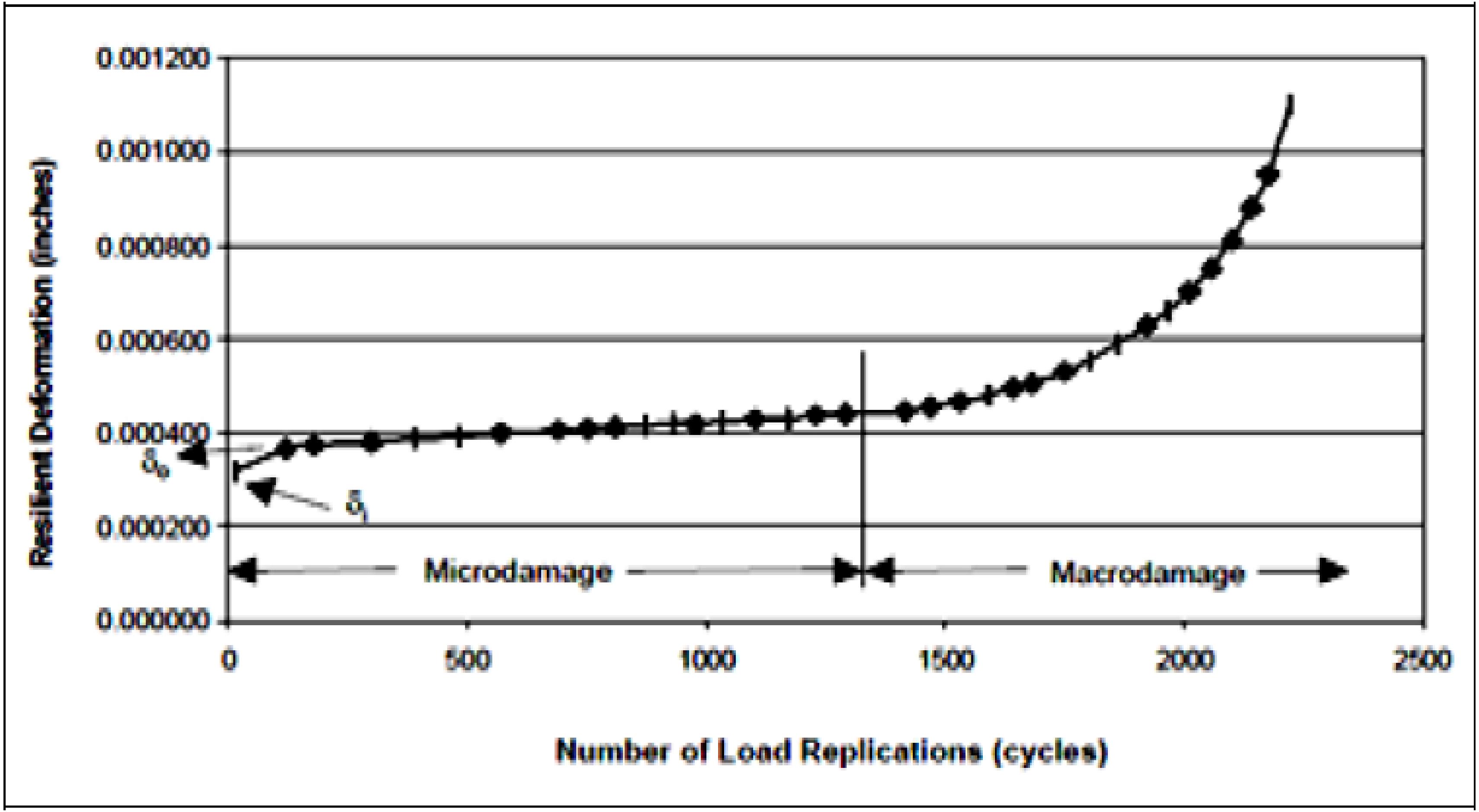
-The rest period may be between each loading cycle or after some loading and rest cycles over a certain period of time.

-During the rest period, relaxation of stresses due to viscoelastic nature of asphalt mixtures and healing takes place.

-longer rest period’s causes greater healing effect and resulting in extended fatigue life of asphalt pavement.

Determination of Failure Limit in the laboratory

The boundary between micro cracking and macro cracking is demonstrated in the following Figure, it shows that macro cracking on the test specimen usually occurred at about 1300 cycles of loading. A conservative cutoff point was to halt loading at 1000 cycles to insure macro cracking had not developed.



0.001200
0.001000
0.000800
0.000600
0.000400
0.000200
0.000000
Resilient Deformation (inches)
δo
δi
Microdamage
Macrodamage
0
500
1000
1500
2000
2500
Number of Load Replications (cycles)

Laboratory evaluation of Asphalt Cement Healing Capabilities

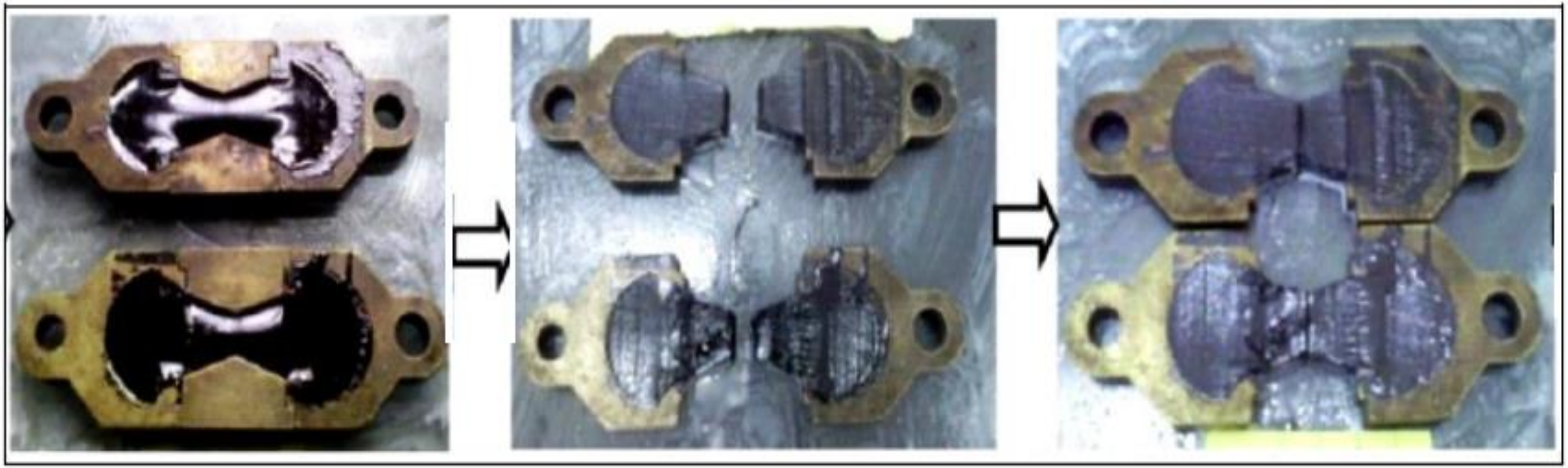
The healing of binders is a three-step process:

1) The closure of micro cracks due to wetting (adhesion of two crack surfaces together driven by surface energy), which is believed to be the fastest, resulting only in the recovery of stiffness.

2) The closure of macro cracks due to consolidating stresses and binder flow.

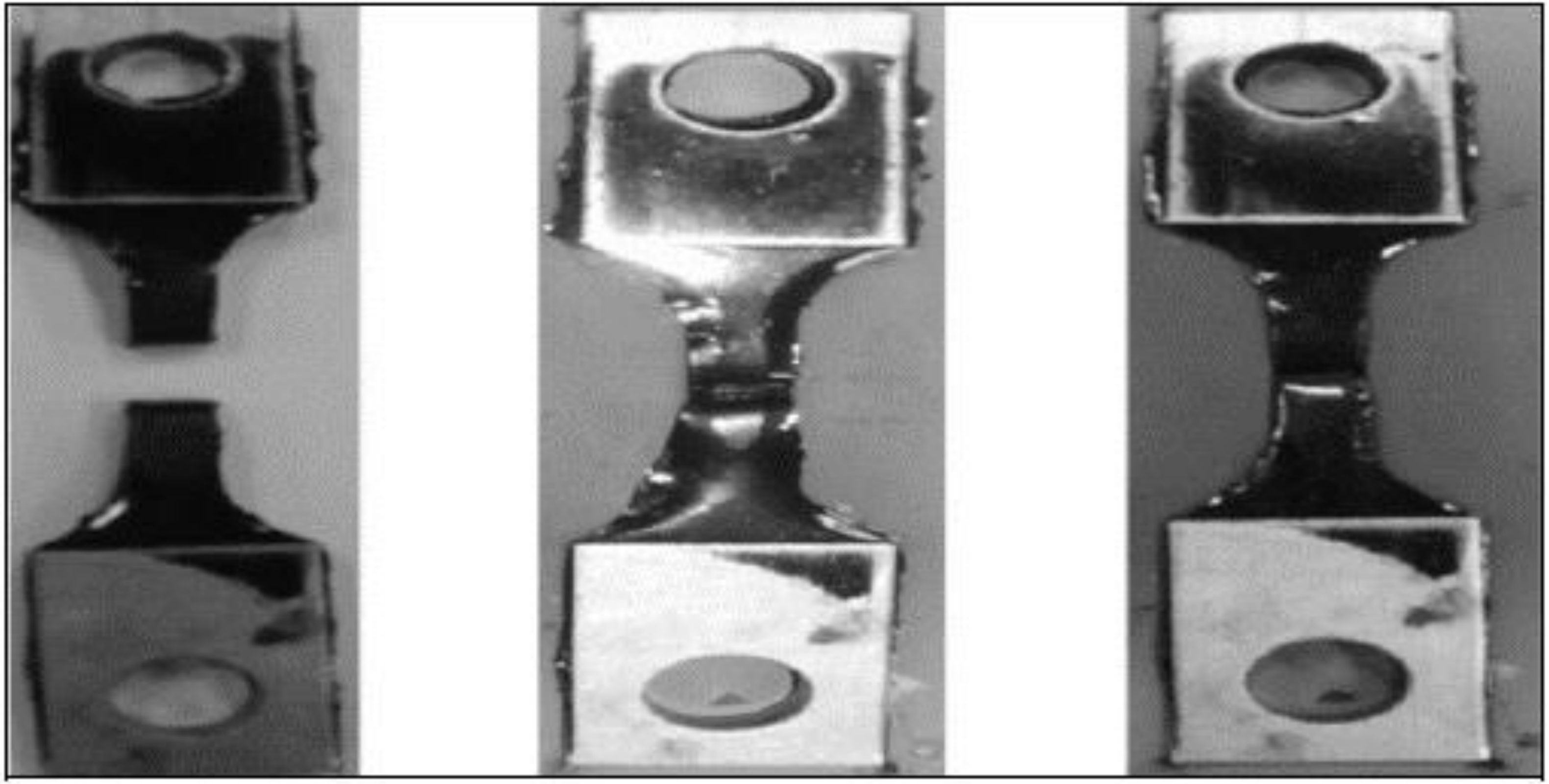
3) The complete recovery of mechanical properties due to diffusion of Asphaltenes structures.

▸▸The Ductility Self-Healing Test

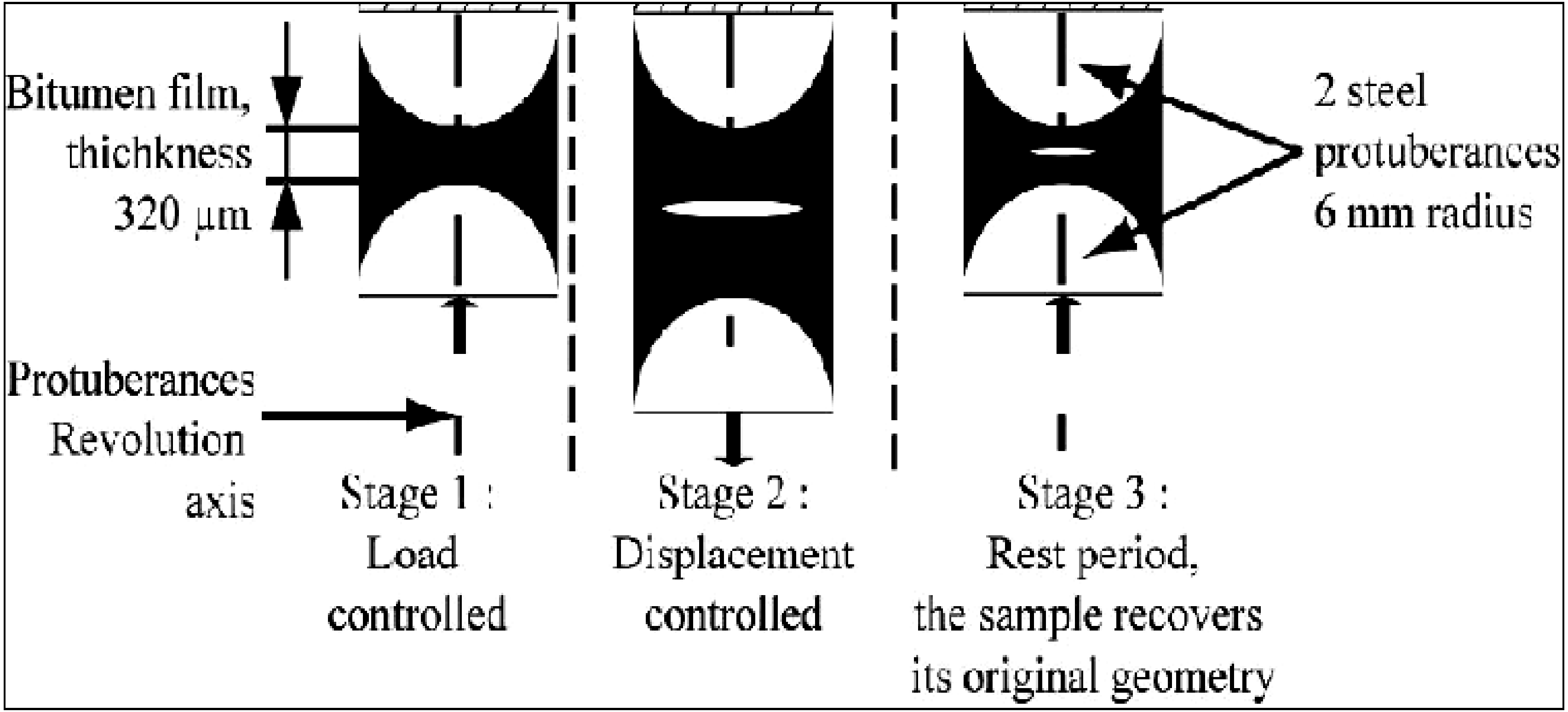


Self-Healing Test using the DSR

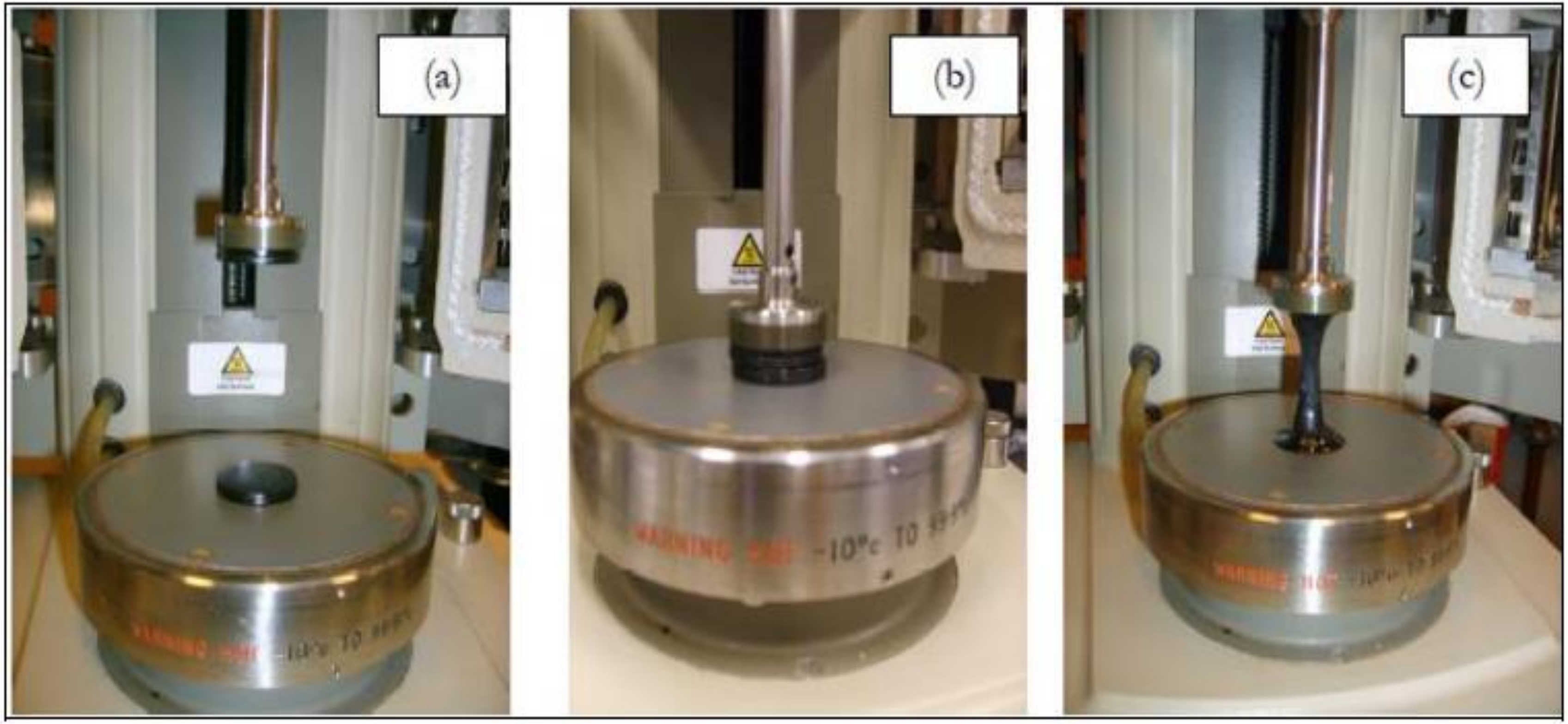
▸▸ Self-healing Test using the DTT with Standard Specimen



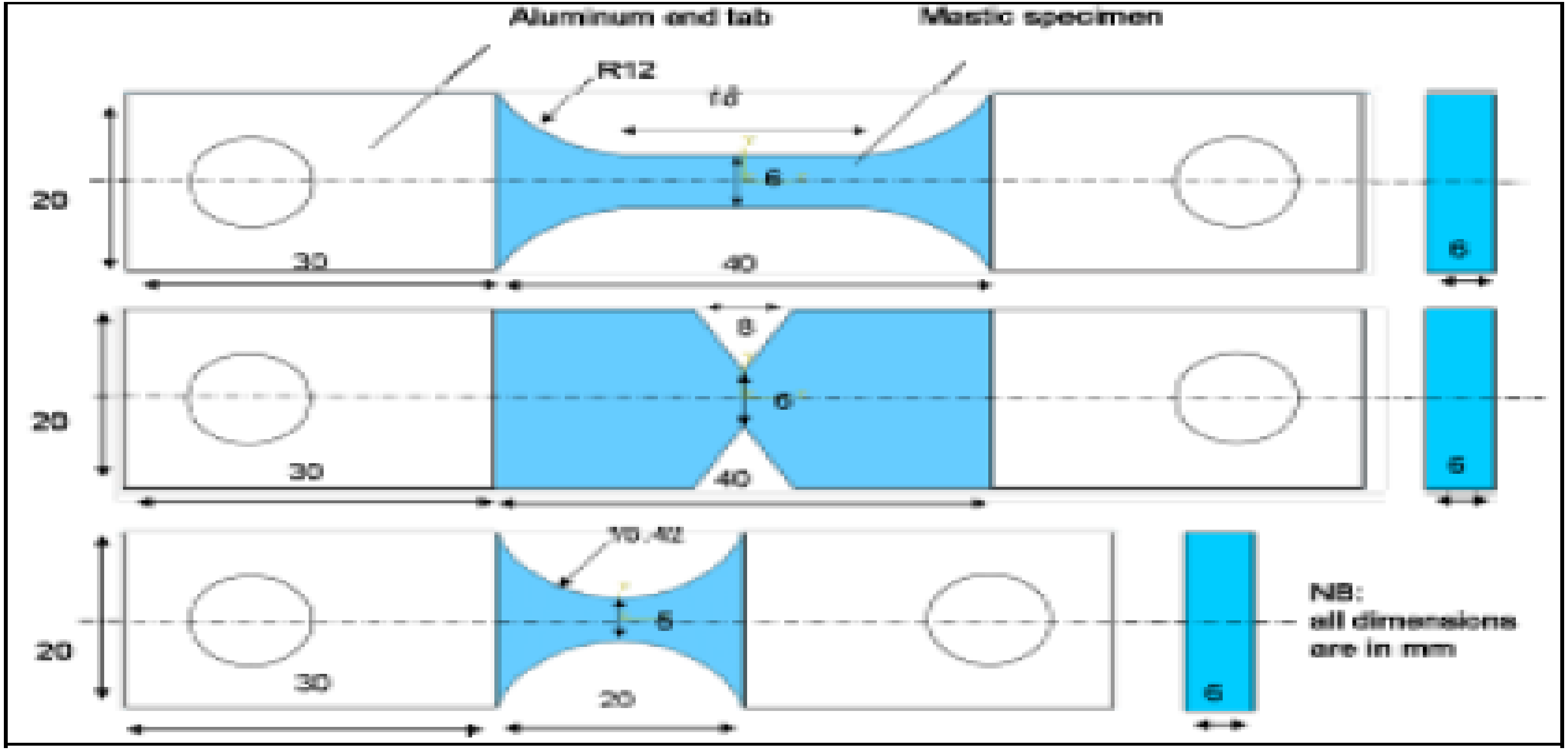
▸▸ Local Fracture Test on Asphalt Cement



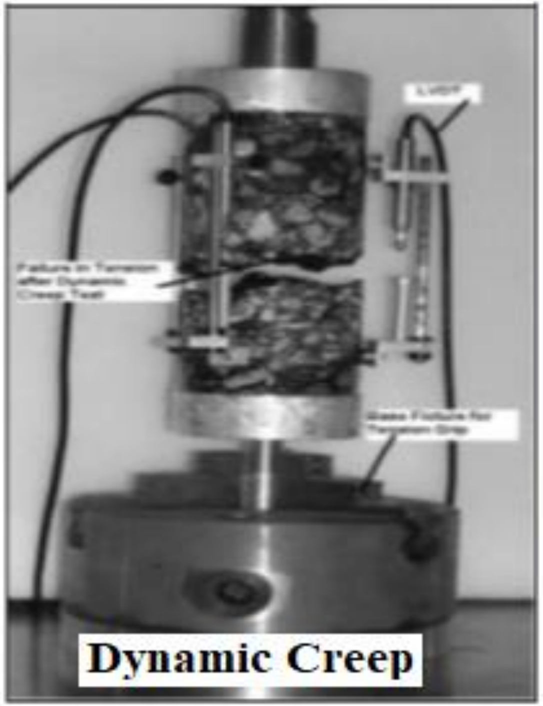
Two Piece Healing Test



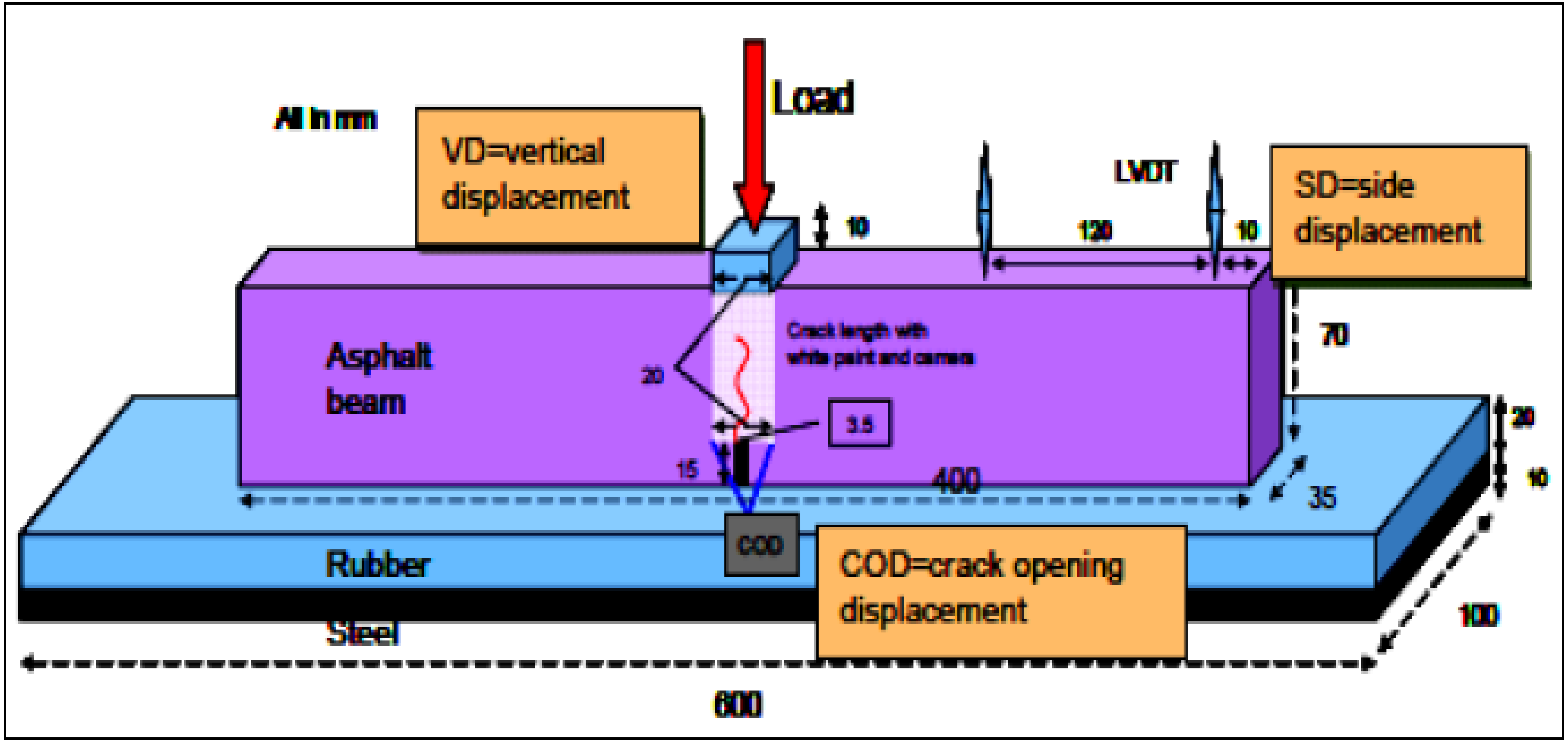
Self-healing Test using the DTT with Modified Specimen



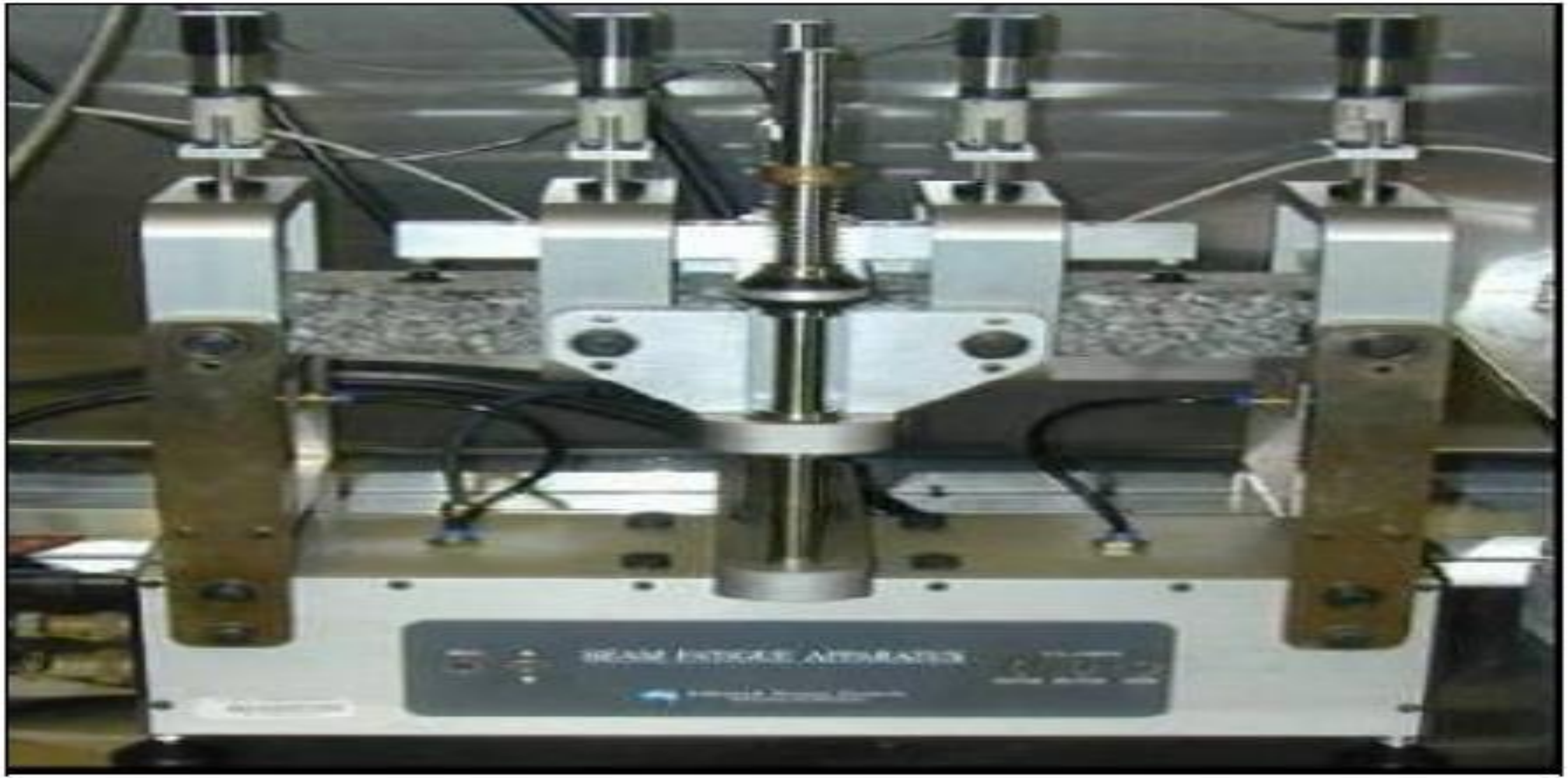
▸▸Mechanical Testing of Asphalt Concrete Healing Capabilities



▸▸ Beam on Elastic Foundation Test (BOEF)



Repeated Flexural Fatigue Beam Test



CONCLUSIONS

1- The sustainability of asphalt concrete pavement could be achieved by considering the micro crack healing process which is very important to enhance the durability of asphalt concrete pavement in terms of fulfilling’s the structural and functional performance.

2- The process of healing can be used to balance the damage process and can be optimized by considering the sensitivity of asphalt concrete to environmental conditions such as; temperature, and material properties.

3- In order for the micro cracks to heal, the asphalt mixture must be allowed to rest for a period of time at temperatures above its glass transition temperature.

4- Bottom-up type of cracks are expected to heal faster than top-down cracks since water damage and Ageing which occur at the pavement surface will reduce the self-healing capability.

5- The amount and rate of healing of asphalt cement depend on several properties such as; its healing potential, stiffness, and surface free energy.

The major contributor to healing is the asphalt binder and mastic component of the mixture.

Recommendation

- It is recommended to consider the self healing concept of asphalt concrete in the design of pavement.
- Laboratory testing to evaluate and improve the self healing ability of binder and asphalt concrete is vital for obtaining a sustainable pavement.

Thank you