Finite Element Approach to Evaluate the Resistance to Plastic Flow in Asphalt Mixtures

Dr. Namir G. Ahmed
Asst. Prof. (Dep. of HWY's & Transp. Eng. University of Al- Mustansiriya)

Dr. Zainab Ahmed Alkaissi
Lecturer (Civil Eng. Dep. University of Al-Mustansiriya)

Suham E. Saleh Al-maliky
Asst. Lecturer. (Dep. of HWY's & Transp. Eng. University of Al- Mustansiriya)

Abstract:

This study is aimed to present theoretical and experimental investigation to evaluate the resistance flow of asphaltic concrete materials. To study theoretically the stability of asphalt mixture, non linear finite element approach has been used. The ANSYS finite element computer program is used to present and simulate asphalt mixture specimens. The finite element solution using ANSYS are compared with experimental tests results. The experimental work includes; Marshall test, furthermore, different factors have been considered in this study. The results of statistical analysis indicate a good agreement is obtained between the experimental and the finite element program results of stability and flow. Comparison with the experimental results indicate that the ability of the finite element program to analyze the behavior of asphalt concrete mixture. The obtained results indicates that the vertical and shear strain increase and reach its maximum value at the edge of specimen, which results in longitudinal cracks originated from the edge and growth along the tested specimen. Also the crack intensity factor is increased which may be attributes to the decrease of horizontal stress and increase of shears stresses that cause the specimen failure.

Key Words: *Finite element, asphalt mixture, stability, flow, Ansys, shear stress, material modeling, theoretical simulation, plastic flow.*

الخلاصة:

هذا البحث يهدف الى تقديم دراسة نظرية ومختبرية لتحري مقاومة الزحف اللدن للاسفلت الكونكريتي.لدراسة ثباتية الخلطة الاسفلتية نظريا ولقد تم استخدام نموذج العناصر المحددة اللاخطي لتحليل الفحوص المختبرية. كما تم استعمال برنامج العناصر المحددة ANSYS لتمثيل الخلطة الاسفلتية. ثم قورنت نتائج برنامج العناصر المحددة مع الفحوص المختبرية والتي تضمنت فحص المارشال مع الاخذ بنظر الاعتبار متغيرات مختلفة. ولقد تبين ان هناك توافق جيد بين الفحوص المختبرية وبرنامج العناصر المحددة لنتائج الثباتية والزحف اعتمادا على التحليل الأحصائي وبينت المقارنة امكانية البرنامج لتحليل تصرف الخلطة الاسفلتية. كما بينت النتائج ايضا ان الانفعال العمودي والقص يتزايد حتى يصل اعلى قيمة له على حافة النموذج مما يسبب التشققات الطولية التي تولدت في حافة النموذج واستمرت على طول النموذج. يضا لوحظ ان معامل التشقق يزداد نتيجة نقصان الاجهاد الافقي وزيادة اجهاد القص مما يسبب فشل النوذج.

1. INTRODUCTION

Asphalt materials represent a difficult medium for the engineer to model due to their complex physical structure and corresponding complex behavior. Stiffness and strength are two fundamental materials properties that are generally required in various engineering materials properties. Designing asphalt mixtures is a complex process and required proper proportioning of materials to satisfy the mechanical properties of asphalt mixtures.

The mechanical performance is a function of stability and strength that can be describing the ultimate state of stress that the asphalt material sustains before it fails.

Most cases and previous studies evaluate the asphalt material behavior based on experimental and fundamental tests. In this research an attempt to study the performance and structural behavior of asphalt material mixtures theoretically and experimentally together.

The Marshall stability test (ASTM D-1559) is used in this research, which is directly measures the stability and flow of a prepared asphaltic concrete specimen. These measures are representative of the plastic flow and failure ultimate load characteristics of bituminous materials those needed for the finite element simulation requirements. For more understanding for the behavior of asphalt materials different factors have been taken into consideration in the experimental work.

2. LITERERATURE REVIEW

Myers et al. (2001) studied the surface-initiated longitudinal wheel path cracking which is also called top-down cracking. This type of cracking is prevalent on high-volume bituminous pavements and has had major cost implications to highway departments. Cores and trench sections taken from pavements exhibit propagation of surface-initiated longitudinal wheel path cracks. The initiation for these cracks is explained by high contact stresses induced under radial truck tires; however the mechanisms for surface crack propagation have not been explained. A combination of finite element modeling and fracture mechanics is selected for physical representation and analysis of a pavement with a surface crack.

Seibi et al. (2001) studied the behavior of asphalt concrete under high rates of loading using uniaxial, triaxial compression and pavement simulation tests. The experimental results of the pavement simulation test and finite element modeling results using **ABAQUS** computer program are used to determine the optimum material parameters.

Siddharthan et al. (2000) used the finite layer mechanistic model taking into consideration important factors such as vehicle speed and the non-uniform stress distribution (normal and shear) at the tire pavement interface. The **3D- MOVE** program developed based on the finite layer formulation can be directed to complete only the required responses.

Sadd et al. (2003) presented a numerical modeling scheme for asphalt concrete based on micromechanical simulation using the finite element method. The load transfer between the aggregate plays a primary role in determining the load carrying capacity and failure of such complex materials. In order to develop a micromechanical model of this behavior, proper simulation of the load transfer between aggregate must be accomplished. The aggregates are taken as rigid particles. In order to properly account for the load transfer between aggregates, it is assumed that there is an effective binder zone between neighboring particles. It is through this zone that the micromechanical load transfer occurs between each aggregate pair and this loading can be reduced to resultant normal and tangential forces and a moment, as shown in **Figure (1).**

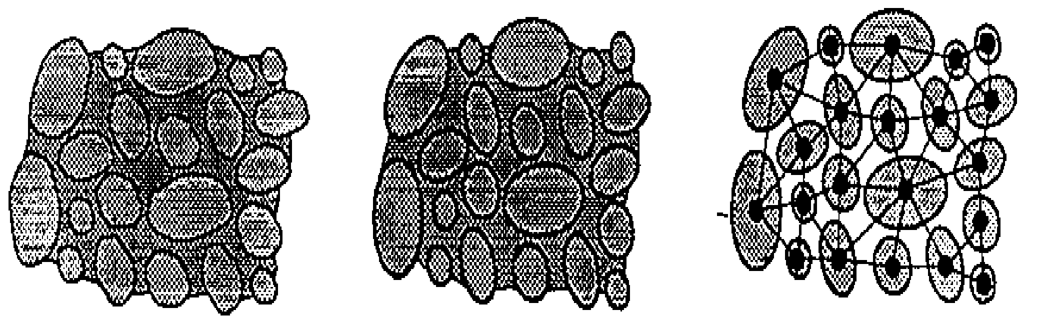

Figure (1) Asphalt Modeling Concept. (After Sadd et al. (2003)).

3. MATERIALS AND EXPERIMETAL WORK

3.1 Materials

In order to evaluate the performance of the selected asphalt mixtures under local conditions, the materials selected are used widely in roads paving in Iraq. The properties of the selected materials are described below.

3.2. Asphalt Cement

The asphalt was taken from the Daurah refinery depending on the magnitude of the standard penetration according to the ***ASTM-D5 (in units of 1/10 mm)***. The penetration and the absolute viscosity of these types of asphalt cement were evaluated as shown in ***Table (1)***, with other physical properties and tests.

3.4. Coarse and Fine Aggregate

The aggregates were taken from ***AL-Nibaee quarry source***. The crushed aggregates gradations was used in this study, as can be seen, a typical dense gradation with a nominal maximum size of aggregate of ***(12.5 mm***). The physical properties and mineral composition are shown in **Tables (2) and (3).**

Table (1): Physical properties of Asphalt Cement.

Test	Units	Asphalt Grade
Penetration (25°C, 100gm, 6 sec) ASTM-D5	(1/10) mm	48
Absolute Viscosity at 60 °C ASTM D2171	Poise	2056
Kinematics Viscosity at 135 °C ASTM D2170	Cst	390
Specific Gravity at 25 °C ASTM – D70	-	1.043
Ductility (25°C; 5 Cm/min) ASTM D113	Cm	120
Flash Point (Cleveland open-cup) ASTM D92	°C	283
Softening Point (°C) Ring and Ball Test ASTM-D36	°C	49
After Thin Film Oven Test		
Penetration of Residue (25°C, 100 g, 5 sec)	(1/10) mm	35
Ductility of Residue (25°C, 5 Cm/min) ASTM D113	Cm	98
Loss in Weight (163°C; 50gm; 5 hrs)	%	0.175

Table (2): Physical Properties of Nibaee Aggregates.

Property	Coarse Aggregate	Fine Aggregate
Bulk Specific Gravity ASTM C-127 and C-128	2.618	2.655
Apparent Specific Gravity ASTM C-127 and C-128	2.693	2.701
Percent Water Absorption ASTM C-127 and C-128	0.486	0.693
Percent Wear (Los Angeles Abrasion) ASTM C-131	24.86	-

Table (3): Mineral Composition of Nibaee Aggregates

Mineral Composition	
% Quartz	82.10
% Calcite	13.82

3.5 Mineral Filler

One type of Filler is used in this work. This type is the cement, from ***AL-Kufa factory***. The physical properties of this filler are presented in Table (4).

Table (4): Physical properties of cement (mineral filler).

Specific Gravity	3.32
% Passing Sieve no. 200	92

4. THEORETICAL ANALYSIS

4.1 Finite Element Methods

The computer oriented finite element method has become one of the most powerful tools in the analysis of the engineering problems. It has unified the analysis of any type of structures under boundary and loading conditions to one basic fundamental procedure. To carry out an analysis of asphalt mixtures behavior, the finite element program ANSYS version (5.4) is used in this study.

The numerical methods such as finite element method used to analyze and calculate the primary response of asphalt materials such as stress, strain and deflection. The complex geometry, meteorology and different loading conditions can efficiently incorporate in the finite element analysis.

The finite element program ANSYS version (5.4) is used to analyze the asphaltic mixtures theoretically and for performance prediction. A plane 42, 2-D structural solid has been adopted in this research. The element can be used as a plane element (plane strain or plane stress) or as an axisymmetric element. The element is defined by four nodes having two degrees of freedom at each node, translations and the nodal x and y directions. The element has plasticity, and large strain capability.

4.2 Simulation of the Material Modeling

The material modeling of asphalt mixtures has been incorporated into the finite element program ANSYS in order to represent an appropriate behavior of asphaltic material. An experimental work is adopted to verify the accuracy of the finite element program ANSYS results.

The Marshall test is performed to evaluate the resistance potential of plastic deformation and the specimen as shown in **Figure (2)** has been simulated using ANSYS. The results of program show the stress and strain distribution within the tested specimen. It is clear from these figures that there is a high gradient of stress and strain on the top and bottom of tested specimen which can be attributed to the applied load on the top and restrained zone at on the bottom that induced high grade of stresses.

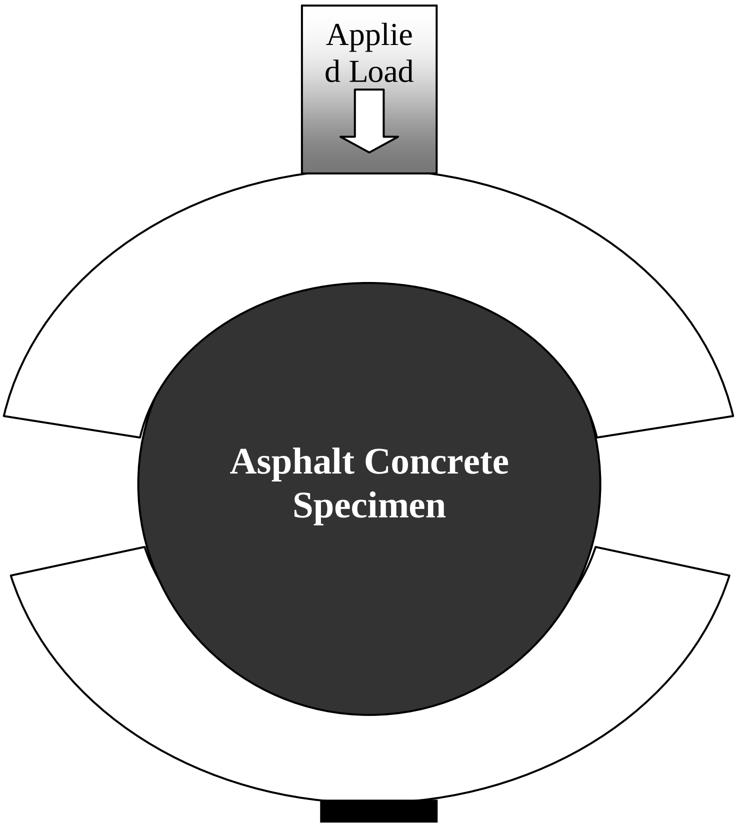

Figure (2): Boundary Condition of Tested Specimen.

4.3 Verification of the Material Modeling

The performance predictions of asphalt mixtures has been incorporated into finite element program ANSYS version (5.4) to evaluate the overall performance of hot mix asphalt mixtures. The input parameters for finite element program are shown in Table (5). The elastic modulus calculated at the first step from the creep test for the specimen and Poisson's ratio is assumed 0.35 as an average value for the asphaltic materials) **(Huang, 1993)**. The cohesion and internal of friction are taken from **(Glanville, 1962)** for asphaltic materials.

Table (5) Material Parameters for Asphaltic Materials

ASPHALT PARAMETERS	**VALUE**					
% Asphalt Content	3.5%	4%	4.5%	5%	5.5%	6%
E (kPa)	1344	1372	1354	1342	1282	1275
ν	0.35					
C(kPa)	158					
ϕ_1 (degree)	26.3					

The marshal flow and stability versus asphalt content plots are obtained from finite element and experimental approach are presented in **Figures (3) and (4)** respectively. A good agreement is obvious between the experimental and the program values of stability and flow. Comparison with the experimental results indicates that finite element modeling with ANSYS program has the ability and recognized to analyze the behavior of asphalt mixture.

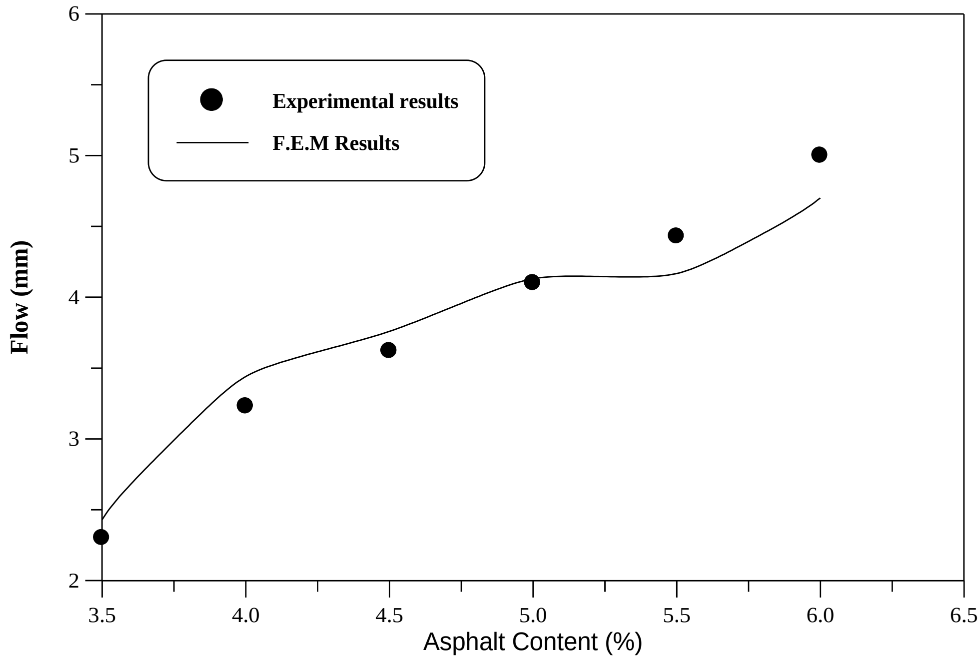

Figure (3): Variation of Flow with Asphalt Content (%).

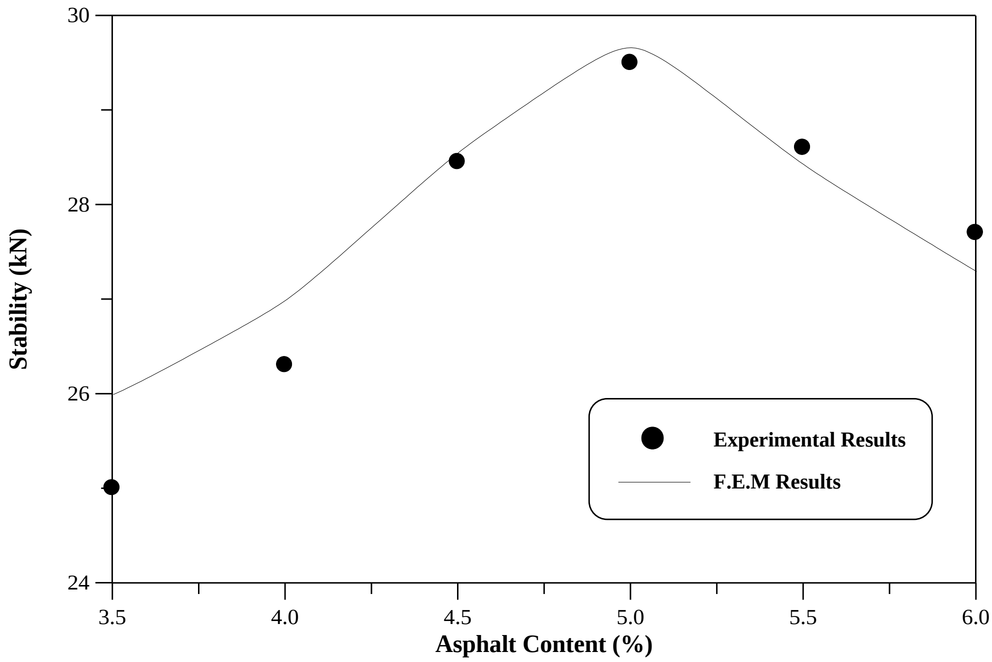

Figure (4): Variation of Stability with Asphalt Content (%).

5. Stress and Strain Distribution

Modeling and simulation of asphalt mixtures specimen were prepared using the finite element program ANSYS (version 5.4) and compared with the experimental specimen after failure. An image to the specimen that fails with Marshall Test was taken to compare with the stress and strain distribution that developed by the finite element program for the simulated specimen. These two pictures were combined to yield the failure or ultimate state both theoretically and experimentally.

The obtained results indicates that the vertical strain, horizontal strain and shear strain was increased and reach its maximum value at the edge of specimen as shown in **Figures (5)**,**(6)** and **(7)** respectively, which results in longitudinal cracks originated from the edge and growth along the tested specimen. **Figures (8)** indicates that the crack intensity factor was increased with the decrease of horizontal stress and increase the shears stresses as shown in **Figures (9)**,**(10) and (11)** respectively. The deformed shape of the tested specimen is shown in **Figure (12)**. While, the failed specimen failure can be seen clearly in the image of tested specimen, that is show in **Figure (13)**.

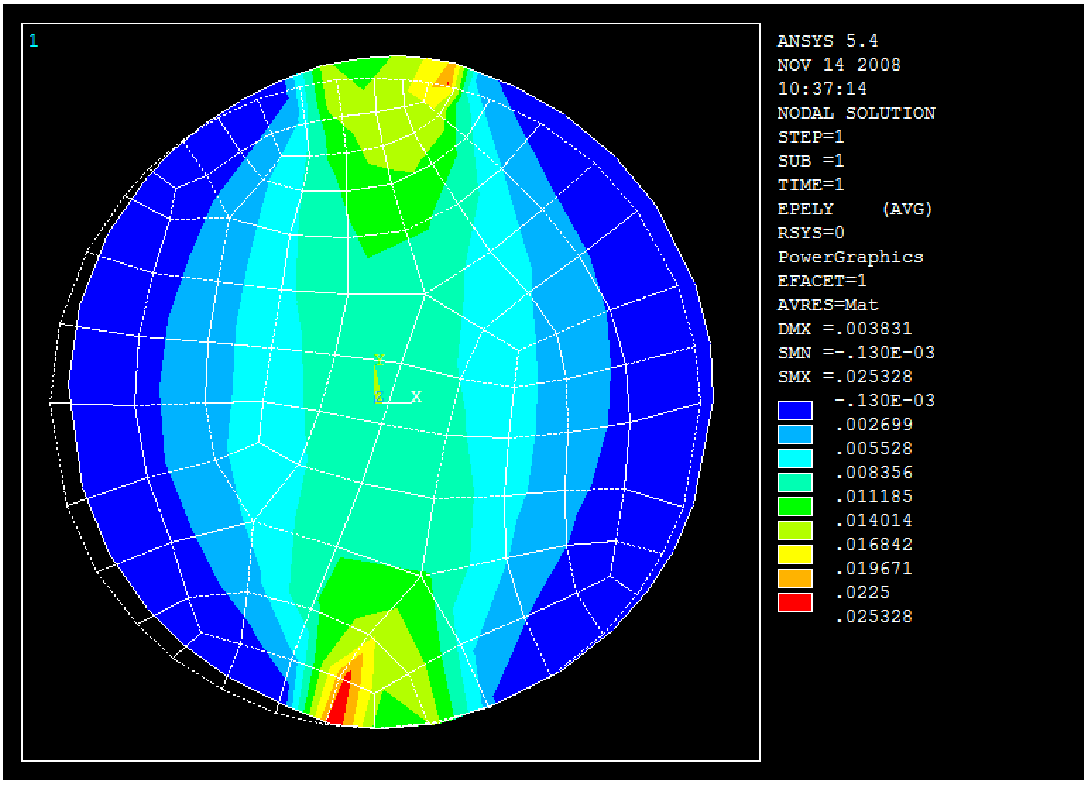

Figure (5): Vertical Strain Distribution of Tested Specimen.

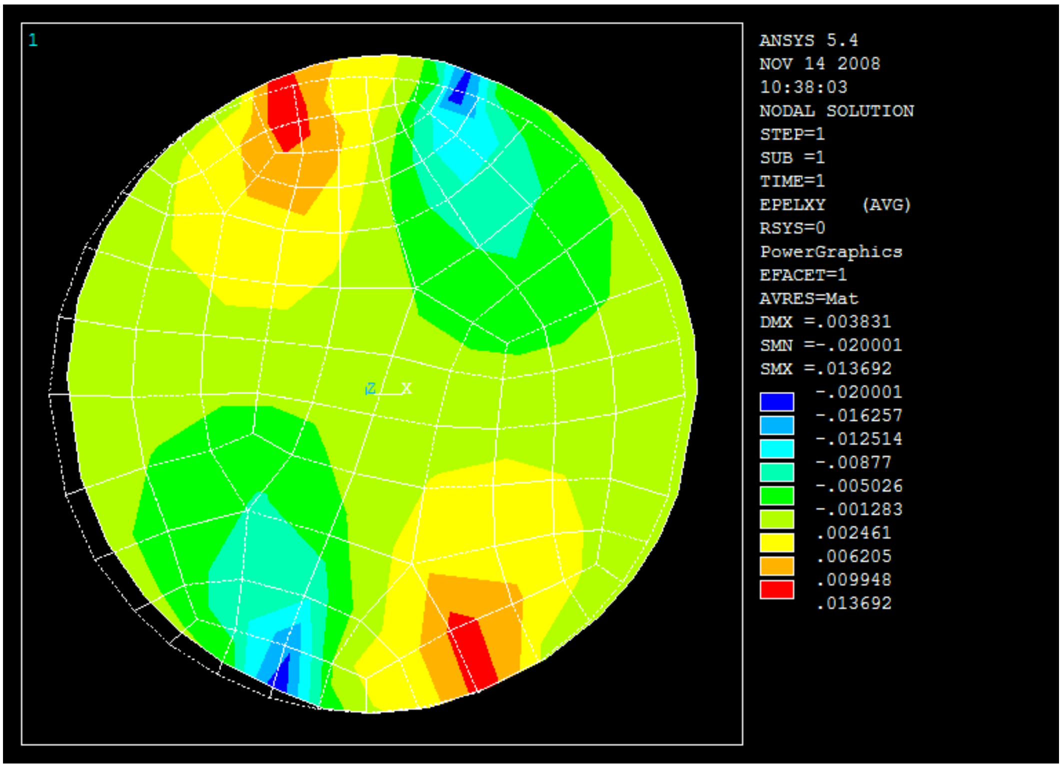

Figure (6): Shear Strain Distribution of Tested specimen.

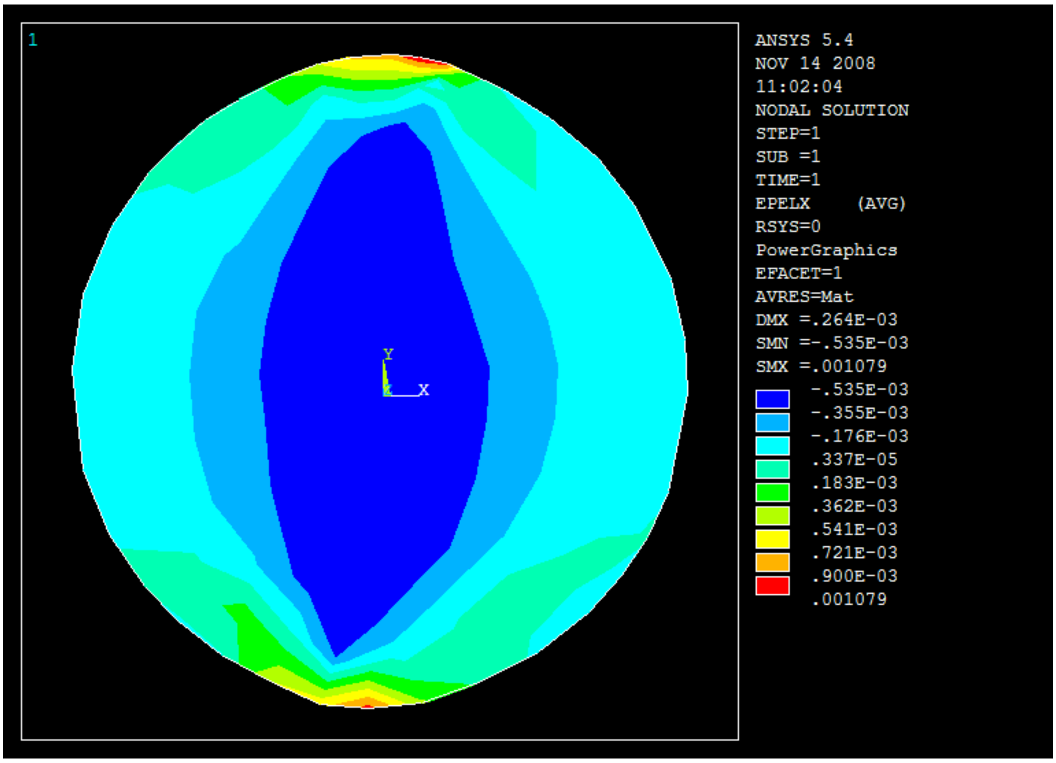

Figure (7): Horizontal Strain Distribution of Tested specimen.

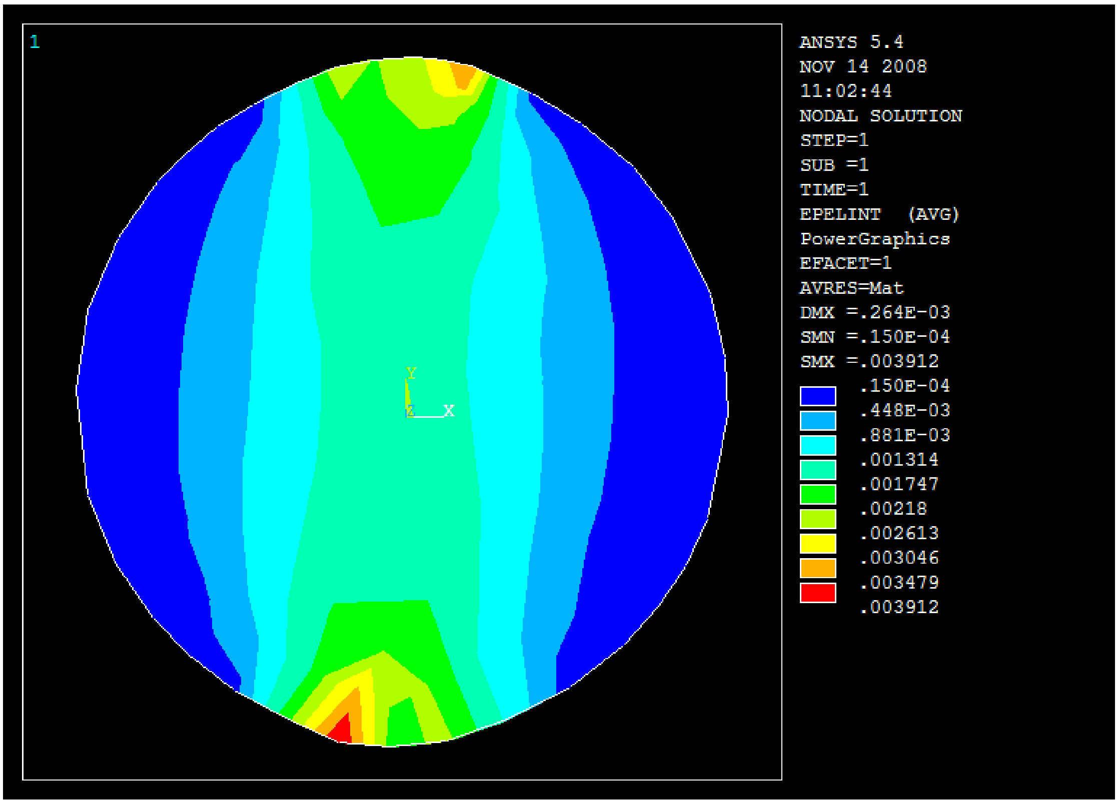

Figure (8): Crack Intensity Factor of Tested specimen.

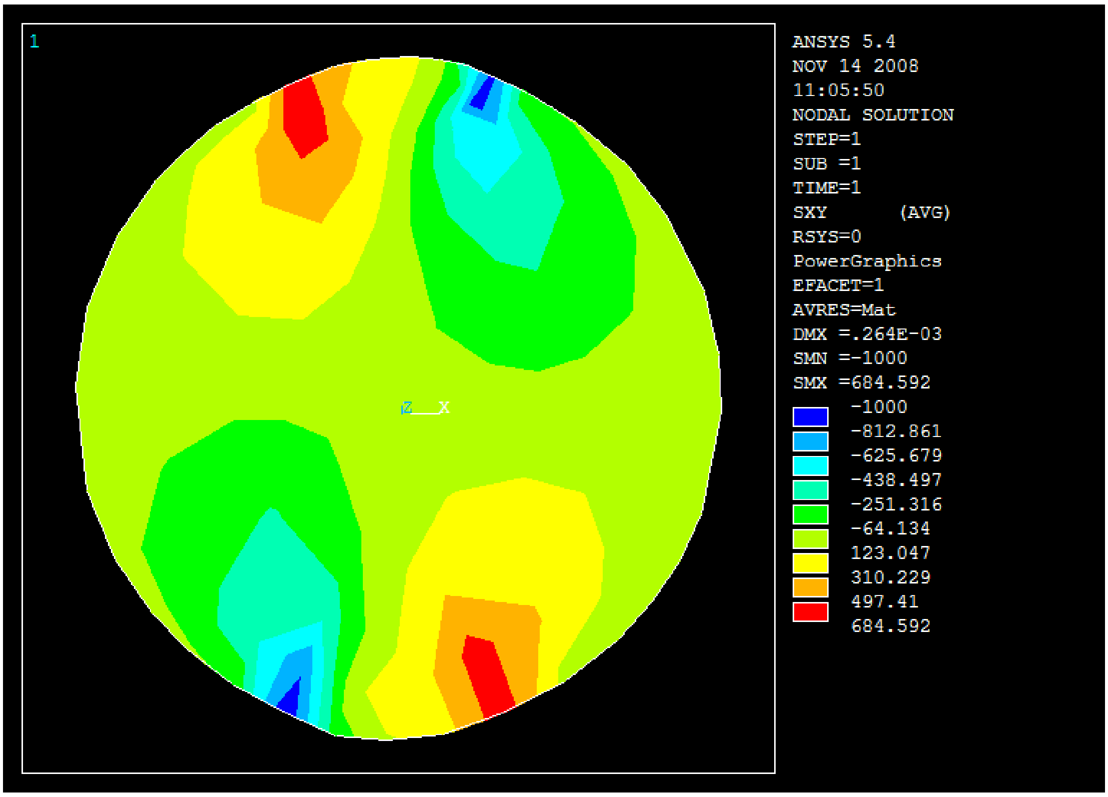

Figure (9): Shear Stress Distribution of Tested specimen.

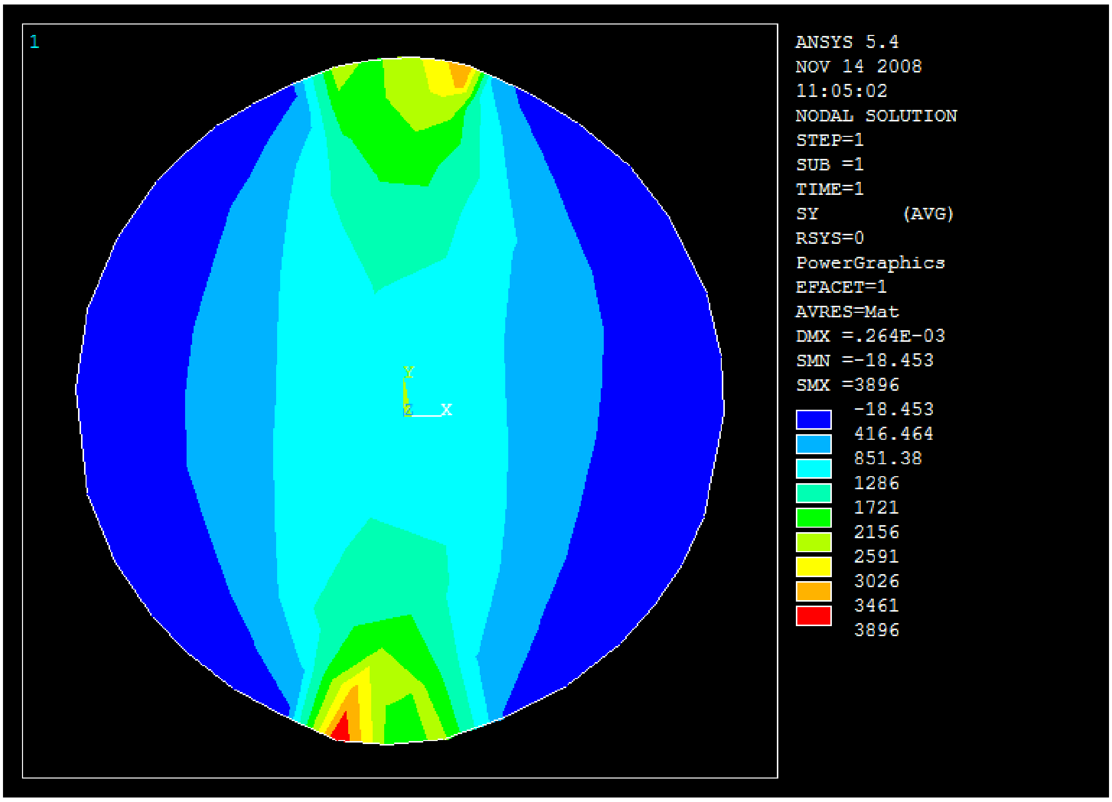

Figure (10): Vertical Stress Distribution of Tested specimen.

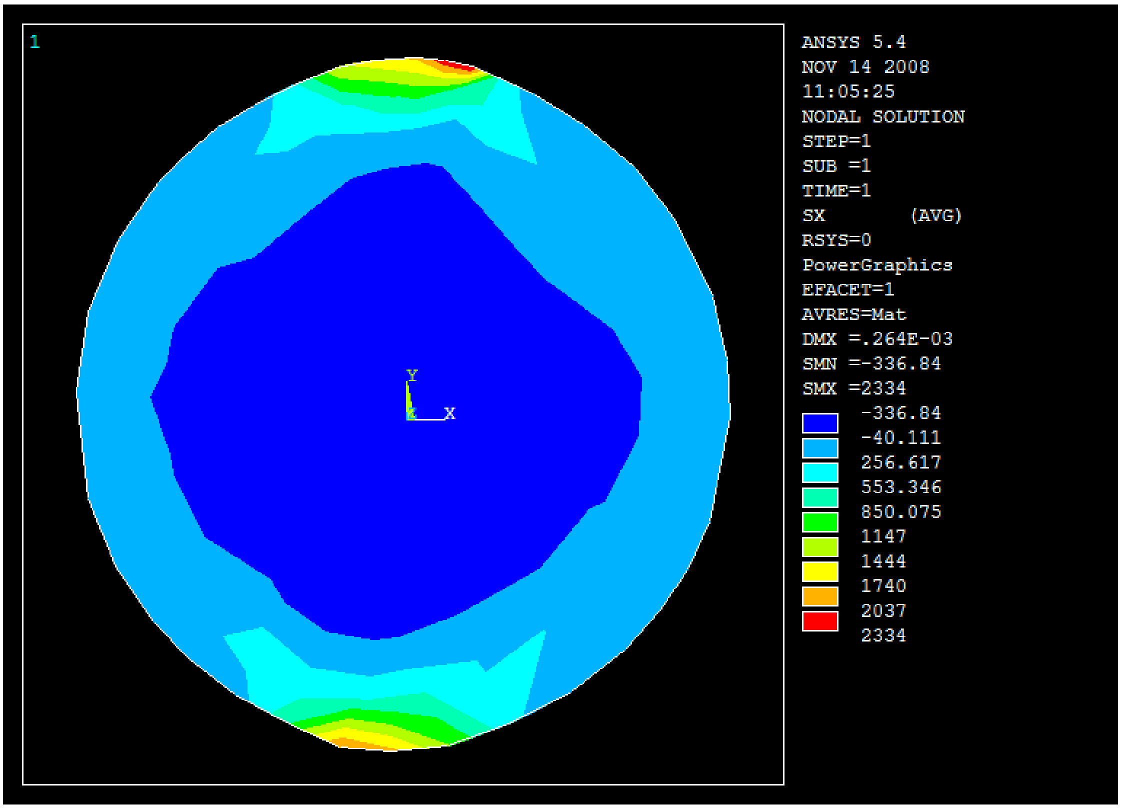

Figure (11): Horizontal Stress Distribution of Tested specimen.

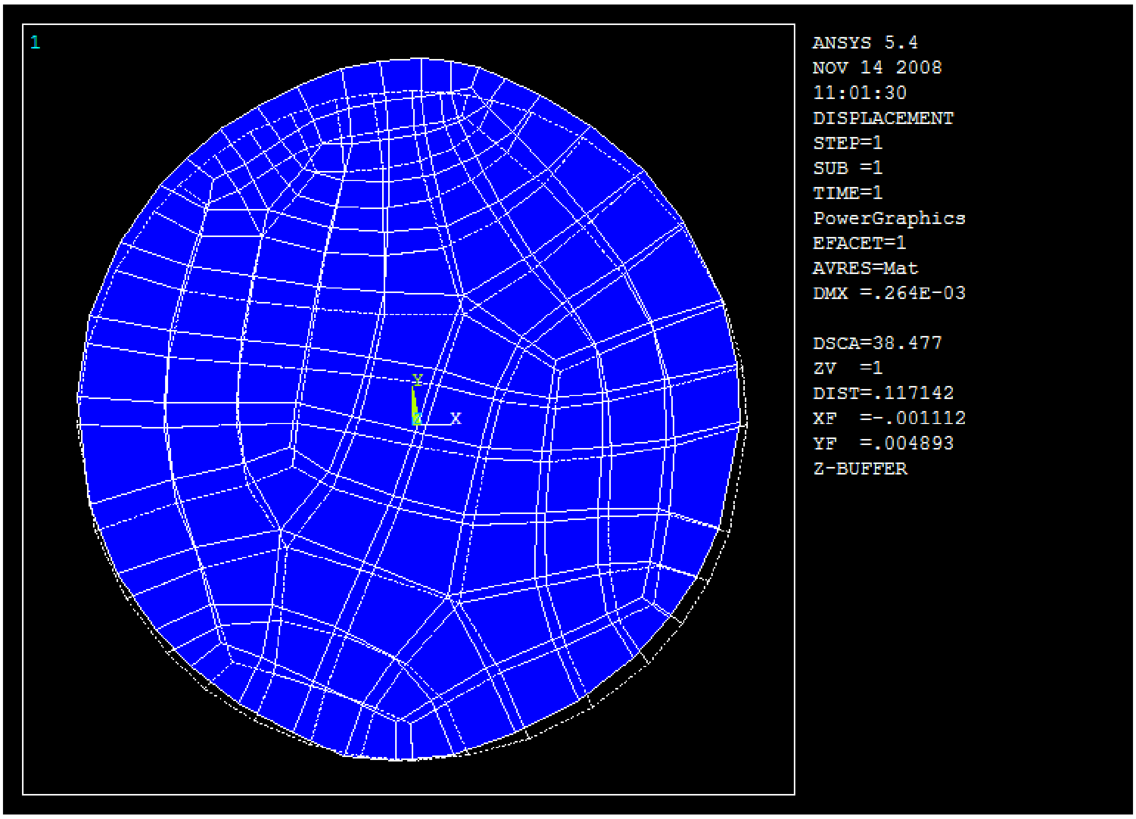

Figure (12): Deformed Shape of Tested specimen.

Plate (13): Images of Failed Specimen.

6-COMPARISION BETWEEN EXPERIMENTAL AND FINITE ELEMENT RESULTS

Table (6) and (7) present the experimental and the finite element results marshal flow and stability of asphalt concrete mixture. While the relation with the function y=x can be seen **in Figure (14) and Figure (15)**.

Good agreement was appeared between the results which obtained by Finite element approach and experimental work.

Table (6): Marshal Flow Results

Asphalt Content %	Exp. Flow (mm)	F.E. results Flow (mm)
3.5	2.43	2.3
4.0	3.44	3.23
4.5	3.75	3.62
5.0	4.13	4.1
5.5	4.167	4.43
6.0	4.7	5

Table (7): Marshal Stability Results

Asphalt Content%	Exp. Stability (kN)	F.E. results Stability (kN)
3.5	26	25
4.0	27	26.3
4.5	28.6	28.5
5.0	29.8	29.6
5.5	28.5	28.6
6.0	27.3	27.8

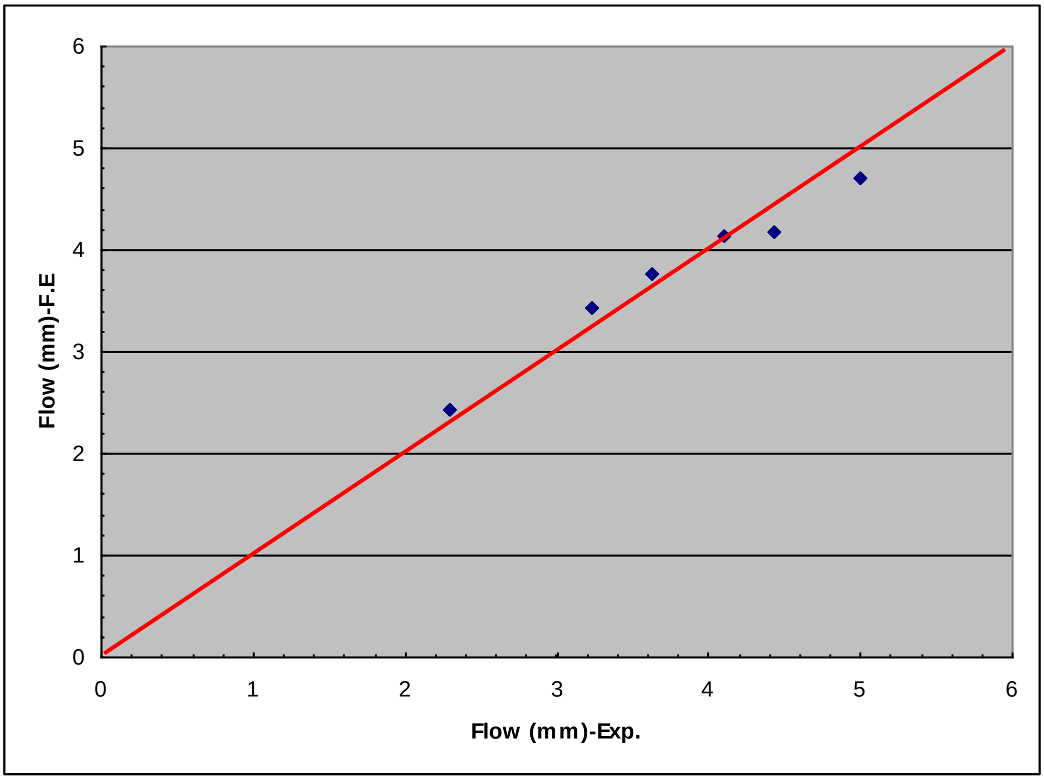

Figure (14): Experimental Versus Finite Element Flow Results .

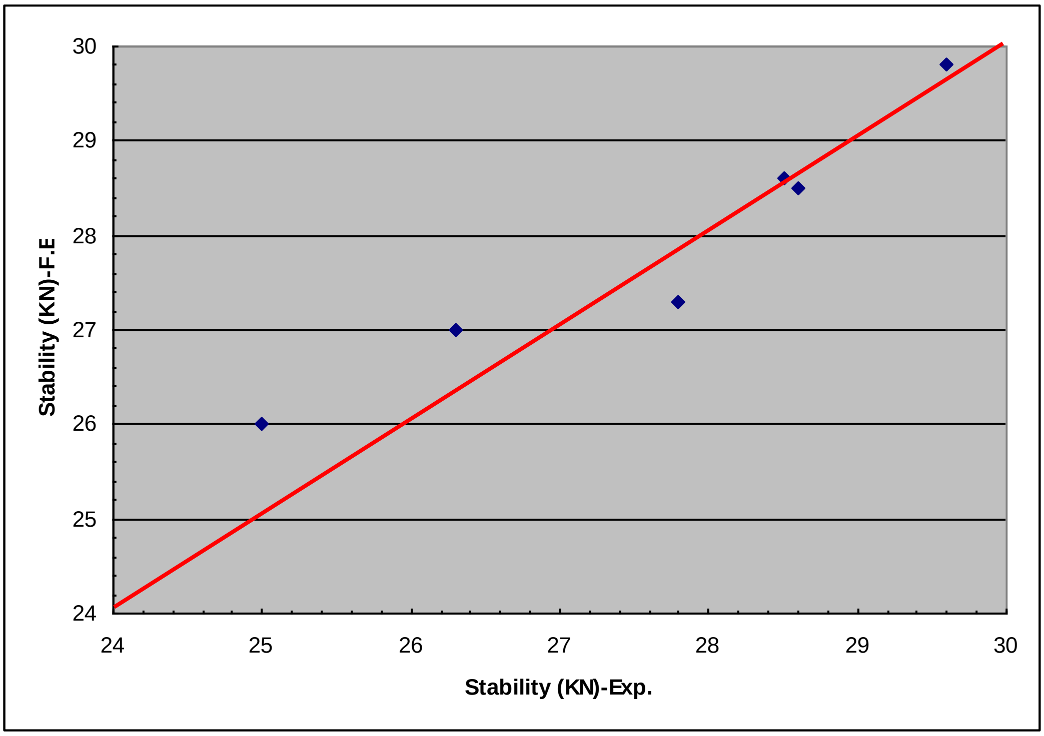

Figure (15): Experimental Versus Finite Element Stability Results

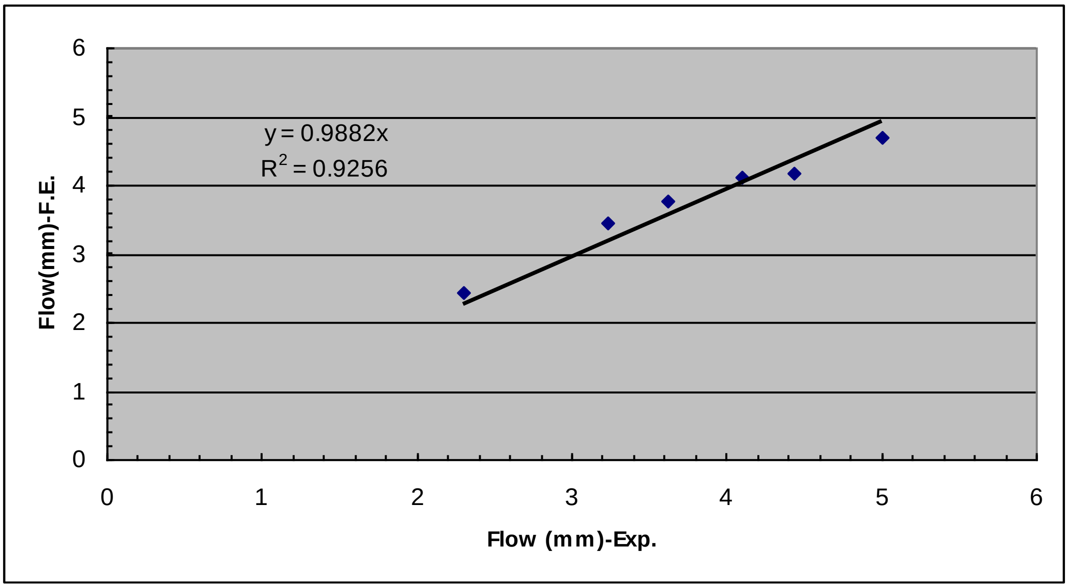

Figure (16): Results versus Exp. Flow and F.E. Flow

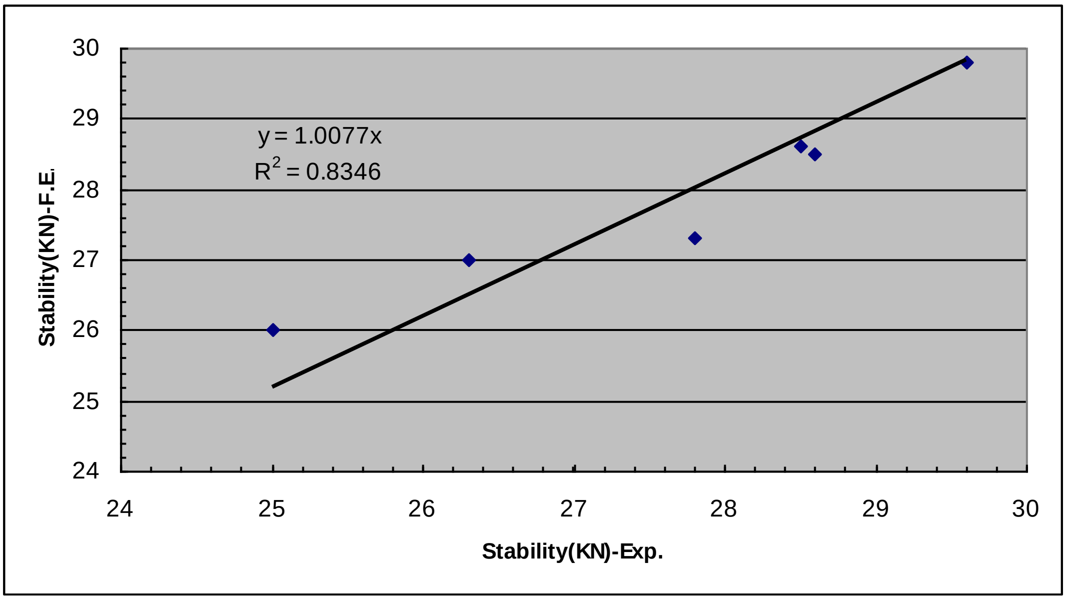

Figure (17): Results versus Exp. Stability and F.E. Stability

The best fit of the relation between the Exp. Flow and F.E. Flow results presented in **Figures (16), (17)** and found in following form:-

F.E. Flow = 0. 9882x ……….. R^2 =0.93

While , it can be found in the following form for the relation between Exp. Stability and F.E. results :

F.E. Stability = 1.0077x ……….. R^2 =0.83

These finding seems to have a good agreement with relation **y=x.**

6.1 Goodness of Fit

To checking the goodness of fit for the finite element and Experimental results . Chi-square test-test were carried out and the following results are expressed.

X^2 –TEST

- **Flow Results**

N=6 , df= 5 , confidence level =95%

Variables	X^2-value	X^2_C - value
X= Exp. Flow	12.54	19.9571
Y= F.E. Flow		

For case $X^2 < X^2_C$ .There is no significant difference between the Exp. and the F.E value.

- **Stability Results**

N=6 , df= 5 , confidence level =95%

Variables	X^2-value	X^2_C - value
X= Exp. Stability	12.54	19.9571
Y= F.E. Stability		

For case $X^2 < X^2_C$. there is no significant difference between the Exp. and the F.E value.

T-test

- **Flow Results**

N=6 , df= 11, confidence level =95%

Variables	mean	St. deviation	T	T_c
X= Exp. Flow	3.78	0.9520	1.00	1.796
Y= F.E. Flow	3.7695	0.7820		

There is no reason to reject the null hypothesis. Thus the difference is no significant between the Exp. and the F.E value.

- **Stability Results**

N=6 , df= 11, confidence level =95%

Variables	mean	St. deviation	T	T_c
X= Exp. Stability	27.633	1.691	1.00	1.796
Y= F.E. Stability	27.867	1.360		

There is no reason to reject the null hypothesis . Thus there is no significant difference between the Exp. and the F.E values.

8. CONCLUSIONS

In this study, an experimental test together with finite element analysis has been performed and an attempt has been made in order to study the behavior of asphalt mixtures theoretically and experimentally; the following conclusions are presented:

1. A good agreement is obtained between the experimental and the finite element ANSYS program results to investigate of ability of asphalt materials to resist plastic flow. Comparisons with the experimental results indicate that the finite element program has the ability to analyze the behavior of asphalt mixture.
2. The results obtained indicates that the vertical and shear strain increase and reach its maximum value at the edge of specimen which results in longitudinal cracks originated from the edge and growth along the tested specimen.
3. The increment of crack intensity factor may be attributed to decrease of horizontal stresses and increase of shear stress that result failure of specimen.

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