

New AASHTO Equivalency Factors of Tracked Armoured Vehicles on Flexible Pavement

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Abstract

Presented in this paper is a study to find new AASHTO equivalency factors of military tracked armoured vehicles on flexible pavement. Two types of military tracked armoured vehicles were studied, namely M1A1 tank and M113A3. A measure of the damaging effect of military tracked armoured vehicle loads was achieved by correlating their equivalent loads with the AASHTO equivalency factors. The equivalent load was developed on the basis of mechanistic - empirical approach. It was found that the damaging effect of the studied military tracked armoured vehicle loads is 0.016 to 19.4 times the damaging effect of the standard 18 kips (80 kN) axle load depending on the thickness of asphalt layer. It was found that the damaging effect of military tracked armoured vehicle loads on flexible pavements of major highways and main principal roads is much more than its damaging effect on the flexible pavement of local and secondary roads. It was found also, that tracked armoured vehicles have a severe damaging effect on the functional serviceability of surface asphalt layer in terms of deformation and strains due to the effect of relatively rigid track chain.

Key Words: Military Tracked Armoured Vehicles, AASHTO Equivalency Factors, Flexible Pavements, and Damaging Effect.

الخلاصة

دراسة جديدة لإيجاد معاملات أشتو لأحمال العجلات المدرعة المسرعة على التبليط الإسفلتي. تم إيجاد معاملات أشتو المكافئة لها ولأول مرة باستخدام طريقة الحل الميكانيكي - التجريبي. لقد وجد إن تأثير الأحمال التخريبي للعجلات المدرعة المسرعة التي تمت دراستها يتراوح من 0.016 إلى 19.4 مرة مقارنة بتأثير حمل أشتو القياسي حسب سمك طبقة الإسفلت. لقد وجد إن تأثير الأحمال التخريبي للعجلات المدرعة المسرعة أكثر بكثير على الطرق الرئيسية مما هو على الطرق الثانوية. لقد وجد إن للعجلات المدرعة المسرعة تأثير تخريبي على الخواص الوظيفية لطبقة الإسفلت السطحية بسبب السرعة الصلبة نسبياً.

1- Introduction

The deterioration of a roadway is accelerated over time by the repeated application of loads generated by heavy vehicles. Research has shown that pavement damage can be more than doubled by axle loads that are only 20 percent over the permitted maximum ⁽¹⁾. The growth in vehicle traffic volumes as observed over the past few decades, combined with increasing commercial vehicle weights and dimensions, is causing the anticipated lifespan of many roadways to decrease. Consequently projected maintenance and preservation costs increase ⁽²⁾. Pavement deterioration is further intensified by an incentive for overweight vehicles due to economic benefits of an increased payload ⁽³⁾. The effect of the traffic using these roads should be focused upon carefully from the standpoint of pavement structural design. Yoder and Witczak ⁽⁴⁾ reported that this effect includes among other considerations, the expected vehicle type and the corresponding number of repetitions of each type during the design life of the pavement. The effect of various types of vehicles (axles) on the structural design of road pavement is considered by means of the approach of axle load equivalency factor. In this approach, a standard axle load is usually used as a reference and the damaging effect of all other axle loads (corresponding to various types of axles) is expressed in terms of number of repetitions of the standard axle.

The AASHTO standard axle is the 18 kips (80 kN) single axle with dual tires on each side ⁽⁴⁾. Thus, the AASHTO equivalency factor defines the number of repetitions of the 18 kips (80 kN) standard axle load which causes the same damage on pavement as caused by one pass of the axle in question moving on the same pavement under the same conditions.

The AASHTO equivalency factor depends on the axle type (single, tandem, or triple), axle load magnitude, structural number (SN), and the terminal level of serviceability (pt). The effect of structural number (SN) and the terminal level of serviceability (pt) are rather small; however, the effect of axle type and load magnitude is pronounced ⁽⁵⁾. There are types of vehicle loads that not included in the AASHTO road test such as the heavy military tracked armoured vehicles that move on paved roads occasionally during peace times and frequently during war times. **The effect of the tracked armoured vehicle loads on flexible pavements is not known, and not mentioned in the literature up to the capacity of the author's knowledge.** Therefore, this research was carried out to find the AASHTO equivalency factors and the damaging effect of tracked armoured vehicles that move frequently on our roads network (even on small local paved streets) on daily bases for more than six years up to now. There are two main approaches used by researchers to determine the equivalency factors, the experimental and the mechanistic (theoretical) approach. A combination of two approaches was also used by Wang and Anderson ⁽⁶⁾. In the mechanistic approach, some researchers adopted the fatigue concept analysis for determining the destructive effect ⁽⁷⁾, while others adopted the equivalent single wheel load procedure for such purposes ⁽⁸⁾. The mechanistic empirical approach is used in this research depending on fatigue concept.

Following Yoder and Witczak ⁽⁴⁾, AASHTO design method recommended the use of 18 kips (80 kN) standard axle with dual tires on each side, thus, the AASHTO equivalency factor F_j is:

$$F_j = \left(\frac{\epsilon_j}{\epsilon_s}\right)^c \dots\dots\dots (1)$$

where, ϵ_j , ϵ_s = the maximum principal tensile strain for the j th axle and the 18 kips standard single axle respectively and c represent regression constants. Yoder and Witczak ⁽⁴⁾ reported that both laboratory tests and field studies have indicated that the constant c ranges between 3 and 6 with common values of 4 to 5.

Van Til et. al. ⁽⁹⁾ and AASHTO ⁽¹⁰⁾ recommended two fatigue criteria for the determination of AASHTO equivalency factors namely, the tensile strain at the bottom fiber of asphalt concrete and the vertical strain on sub-grade surface. AASHTO ⁽¹⁰⁾ reported a summary of calculations for tensile strain at the bottom fiber of asphalt concrete (as fatigue criterion) due to the application of 18 kips standard axle load on flexible pavement structures similar to that of original AASHTO road test pavements. Also, AASHTO ⁽¹⁰⁾ reported a summary of calculations for vertical compressive strain on sub-grade surface (as rutting criterion) due to the application of 18 kips standard axle load on flexible pavement structures similar to that of original AASHTO road test pavements.

The AASHTO ⁽¹⁰⁾ calculated strains are function of the structural number (SN), the dynamic modulus of asphalt concrete, the resilient modulus of the base materials, the resilient modulus of roadbed soil, and the thickness of pavement layers. These reported AASHTO ⁽¹⁰⁾ strains which represent (ϵ_s) in equation (1) above in addition to Van Til et. al. ⁽⁹⁾ & Huang ⁽¹¹⁾ reported experimental values for the constant c in equation (1) above for different pavement structures. Huang ⁽¹¹⁾ reported that in fatigue analysis, the horizontal minor principal strain is used instead of the overall minor principal strain. This strain is called minor because tensile strain is considered negative. Horizontal principal tensile strain is used because it is the strain that causes the crack to initiate at the bottom of asphalt layer. The horizontal principal tensile strain is determined from:

$$\epsilon_r = \frac{\epsilon_x + \epsilon_y}{2} - \sqrt{\left(\frac{\epsilon_x - \epsilon_y}{2}\right)^2 + (\gamma_{xy})^2} \dots\dots (2)$$

where, ϵ_r = the horizontal principal tensile strain at the bottom of asphalt layer, ϵ_x = the strain in the x direction, ϵ_y = the strain in the y direction, γ_{xy} = the shear strain on the plane x in the y direction. Therefore, (ϵ_r) of equation (2) represents (ϵ_j) of equation (1) and will be used in fatigue analysis in this research. These two criteria were used in this research to determine the AASHTO equivalency factors of tracked armoured vehicles.

The tensile strains at the bottom fiber of asphalt concrete and vertical compressive strains on sub-grade surface of similar pavement structures to that of AASHTO road test as reported by AASHTO ⁽¹⁰⁾ were calculated under tracked armoured vehicles in this research. Also, a comparison was made between different calculated three-direction strains under tracked armoured vehicles on the surface of flexible pavement and that of AASHTO 18 kips standard axle to study the damaging effect of these tracked armoured vehicles on the functional features of the asphalt layer. KENLAYER linear elastic computer program ⁽¹¹⁾ was used to calculate the required strains and stresses in this research at 400 points each time in three dimensions at different locations within AASHTO reported pavement structures under tracked armoured vehicles.

2- Characteristics of tracked armoured vehicles

Two types of military tracked armoured vehicles were used in this research, namely, Abrams M1A1 tank and M113A3 armoured vehicle because they are widely used world wide. The characteristics of tracked armoured vehicles which required in this research are their three dimensions (height, length, and width) in addition to weights. The width and length of the tracked armoured vehicle track in contact with the surface of flexible pavement are required, also. These features were obtained from the brochure of the manufacturing company ^(12&13) and the website ⁽¹⁴⁾. The width and the length of the track in contact with the surface of asphalt pavement were measured from the available tracked armoured vehicle markings on the surface of asphalt concrete pavements at different locations.

Figure (1), Table (1), Figure (2), and Figure (3) were prepared to show the obtained characteristics of the two military tracked armoured vehicles. It was found that the actual track width of the M1A1 tank (in contact with the surface of asphalt pavement) is 24 inch (61 cm) to 28 inch (71 cm) on each side. This track is not in full contact with the pavement, there are openings depending on the type and way these tracks are manufactured as shown in Figure (1). Therefore, the effect of the shape and width of the track contact area will be studied to investigate their effect on the results.



Abrams M1A1 military tank



M113A3 Multipurpose military light tracked armoured vehicle

Figure (1): Tracked armoured vehicles ^{(12),(13) & (14)}.

Table (1): Characteristics of tracked armoured vehicles ^{(12),(13) & (14)}.

Feature	Type of tracked armoured vehicle	
	M1A1	M113A3
Length (m)	7.93	4.86
Width (m)	3.66	2.69
Height Turret (m)	2.89	2.20
Combat Weight (ton)	69.05	17.25
Max. Speed (km/h)	70	65

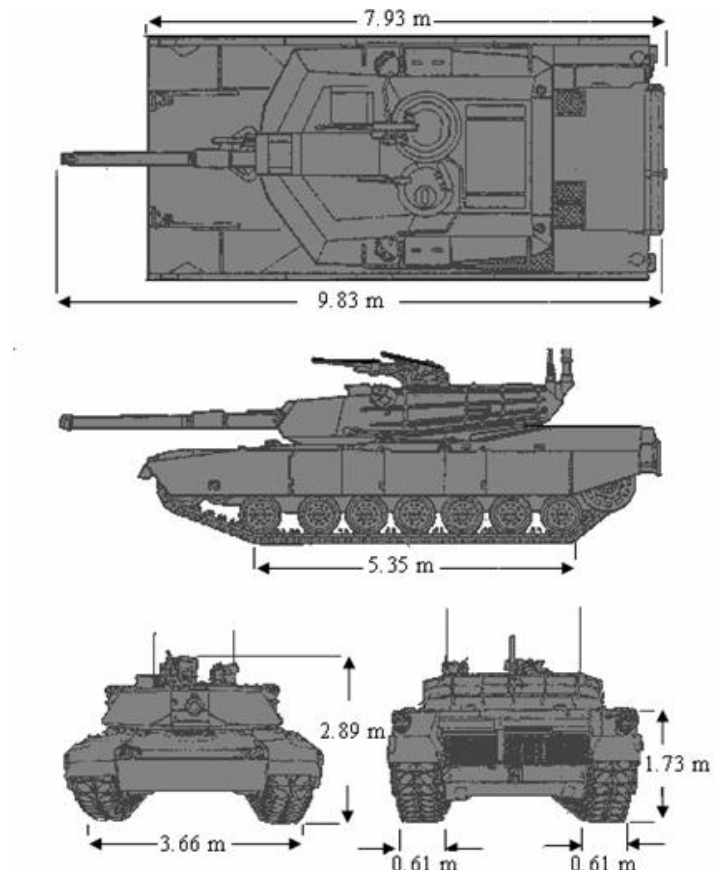


Figure (2): Dimensions of tracked armoured vehicle M1A1 tank ^{(12),(13) & (14)}.

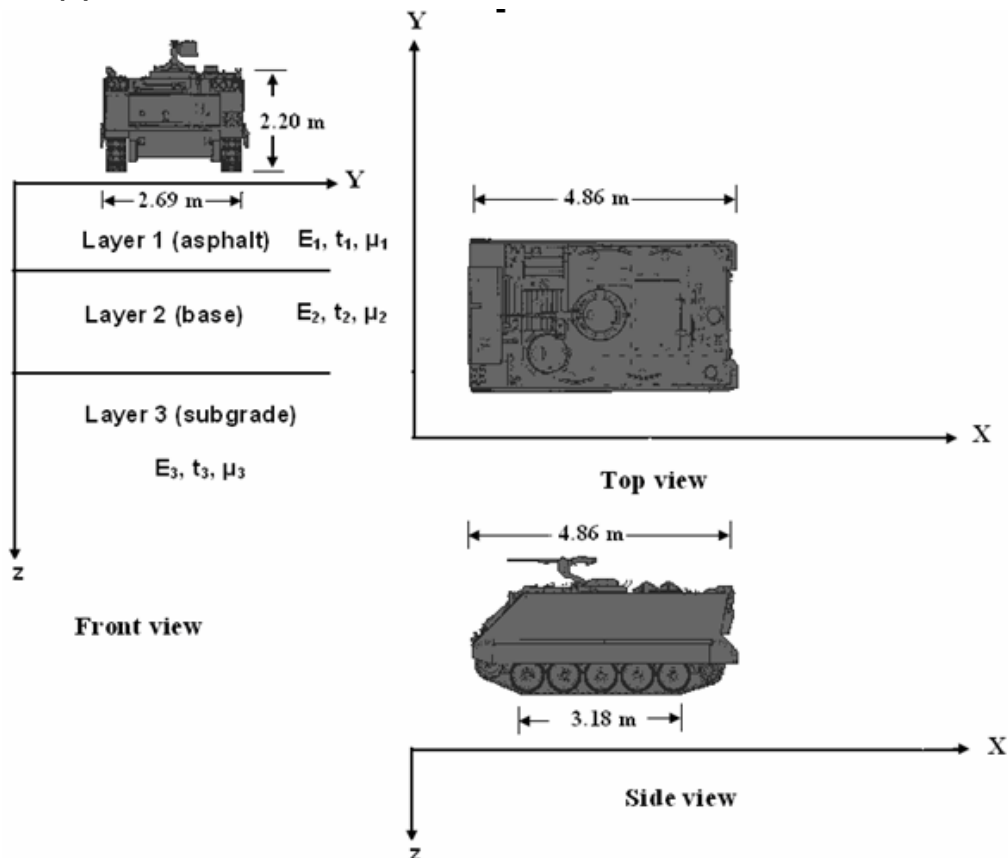


Figure (3): Dimensions of tracked armoured vehicle M113A3 ^{(12),(13) & (14)}.

3- Analysis Methodology

3-1 The simulation of military tracked armoured vehicle load

3-1-1 The simulation of M1A1 tank load

The length of the track of the M1A1 tank that in direct contact with the ground was taken as 5.35 m as shown in Figure (2) above. This length value was obtained from the brochure of the manufacturing company ⁽¹²⁾ and the website ⁽¹⁴⁾ in addition to that this width value was found to be almost equal to that measured from markings left on the surface of asphalt layer at different locations. Two values for the width of the M1A1 track were taken in the analysis namely, 0.61 m and 0.71 m because when the tracked armoured vehicle moves on soft ground (earth surface), the whole width of the track (0.71 m) is involved in transferring the tracked armoured vehicle loads but when it moves on paved roads the inner solid plates of the track (0.61 m) are involved mainly in transferring the tracked armoured vehicle load to the ground, see Figure (1) above.

Two types of contact area were taken in this analysis to simulate the distribution of tracked armoured vehicle loads on the surface of flexible pavement for analysis purposes, as shown in Figures (4) below. The first type shown in Figure (4) represents the (0.61 m x 5.35 m) track on each side of the tracked armoured vehicle. This track contact area (on each side of the M1A1 tank) was simulated by 40 circular areas with a radius of (0.096 m) each to take the contact solid plates of the track into consideration and to keep the same M1A1 tank load without change. The second type shown in Figure (4) represents the (0.71 m x 5.35 m) track on each side of the M1A1 tank load. This track area was simulated by 9 circular areas on each side of the M1A1 tank with a radius of (0.29 m) each to take the maximum contact width of the track into consideration and to keep the same M1A1 tank load without change.

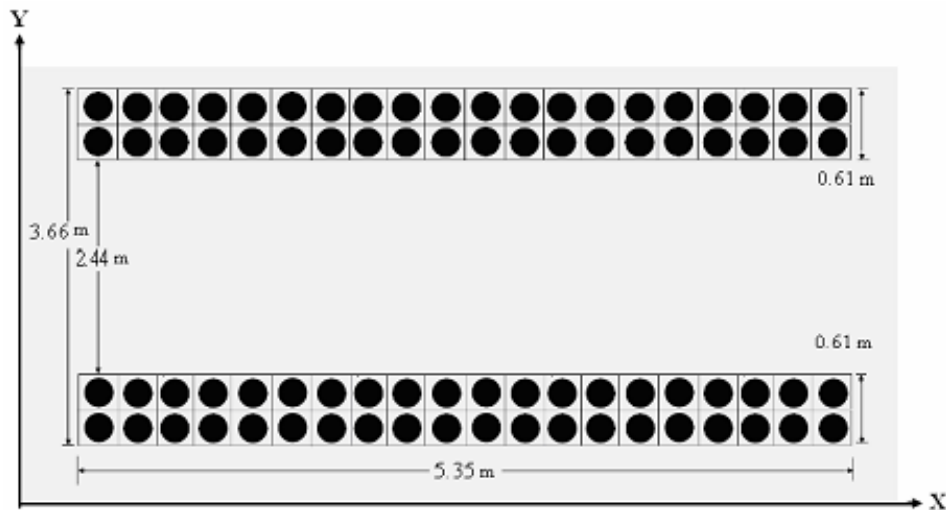
3-1-1 The simulation of M113A3 military tracked armoured vehicle load

M113A3 multipurpose armoured vehicle was used as the second type of military tracked armoured vehicles that is widely used world wide ⁽¹⁴⁾. The length of the track of the M113A3 armoured vehicle that in direct contact with the ground was taken as 3.18 m as shown in Figure (3) above.

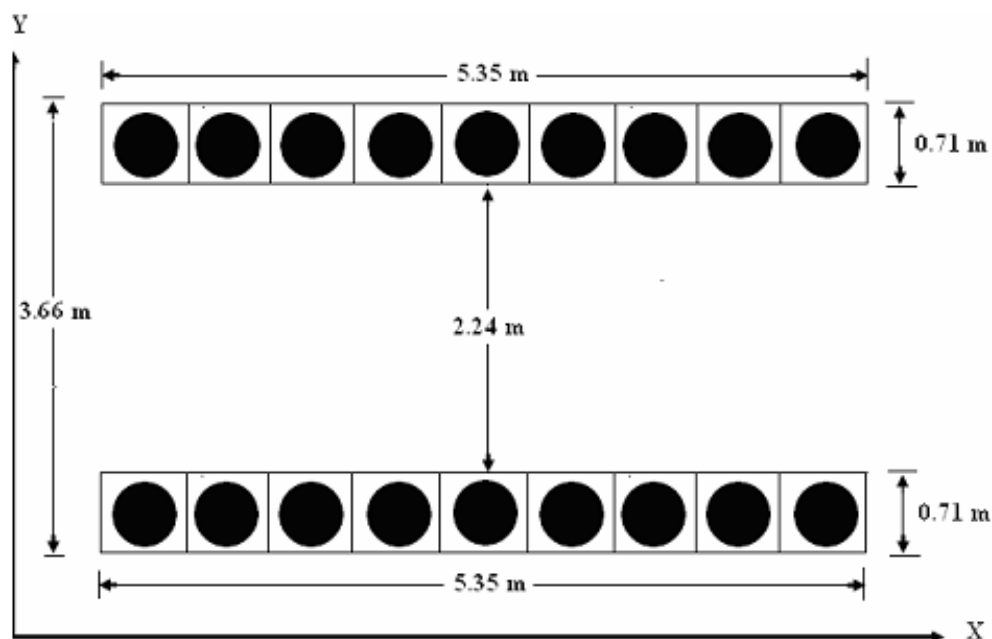
This length value was obtained from the brochure of the manufacturing company ⁽¹³⁾ and the website ⁽¹⁴⁾ in addition to that; this width value was found to be almost equal to that measured from markings left on the surface of asphalt layer at different locations. Two types of contact area were taken in the analysis to simulate the distribution of M113A3 armoured vehicle loads on the surface of flexible pavement for analysis purposes, as shown in Figures (5) below.

The first type shown in Figure (5) represents the (0.35 m x 3.18 m) track on each side of the M113A3 armoured vehicle. This track contact area (on each side of the M113A3 armoured vehicle) was simulated by 40 circular areas with a radius of (0.078 m) each to take

the contact solid plates of the track into consideration and to keep the same M113A3 armoured vehicle load without change. The second type shown in Figure (5) represents the (0.55 m x 3.18 m) track on each side of the M113A3 armoured vehicle. This track area was simulated by 9 circular areas on each side of the M113A3 armoured vehicle with a radius of (0.176 m) each to take the maximum contact width of the track into consideration and to keep the same M113A3 armoured vehicle load without change.



Type1 simulation of the distribution of M1A1 tank loads



Type2 simulation of the distribution of M1A1 tank loads

Figure (4): Type1 and 2 simulation of the distribution of M1A1 loads on the surface of flexible pavement for analysis purposes.

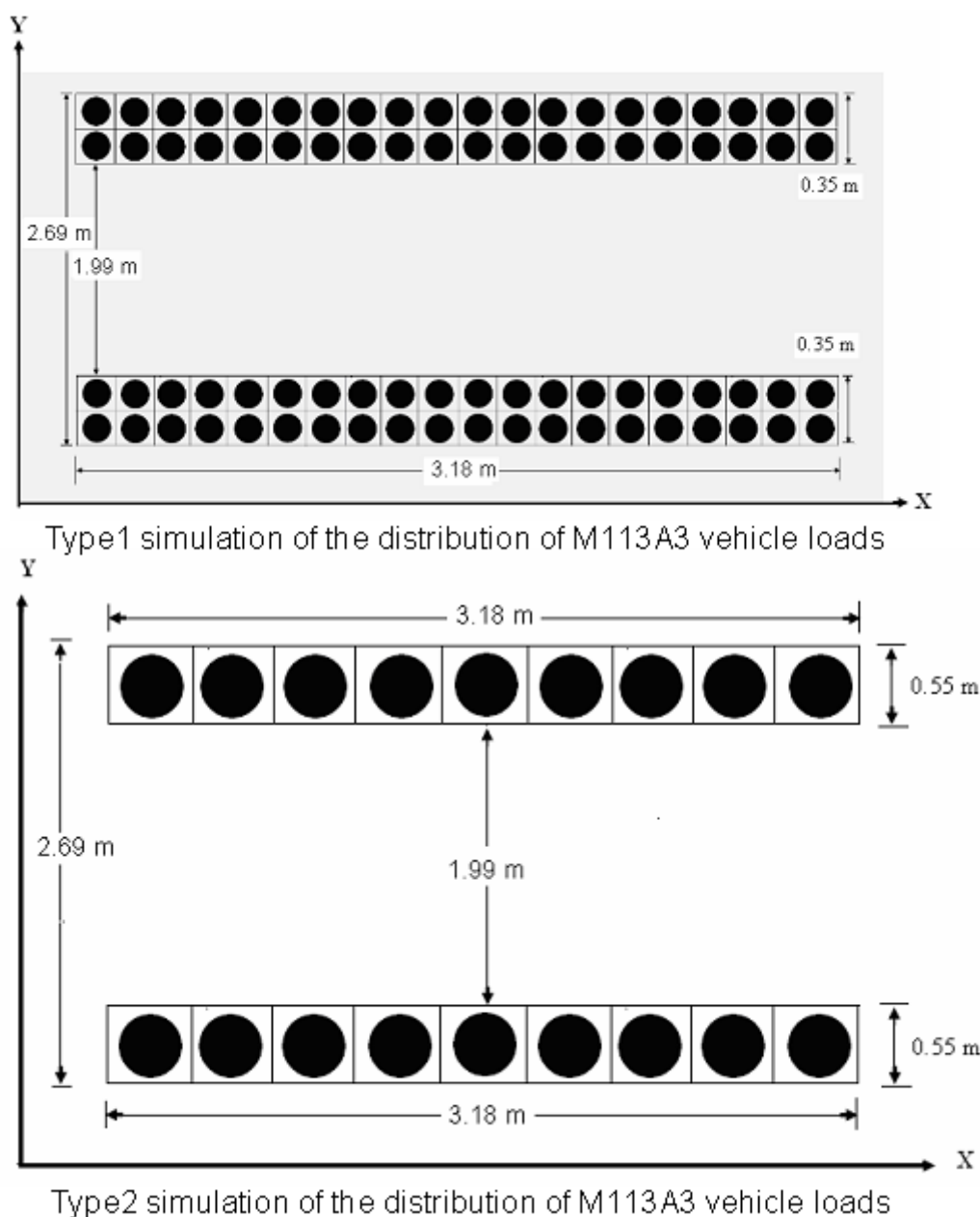


Figure (5): Type 1 and 2 simulation of the distribution of M113A3 loads on the surface of flexible pavement for analysis purposes.

3-2 AASHTO equivalency factors of military tracked armoured vehicles

Three-layer pavement structure was taken as mentioned in the introduction above to simulate AASHTO original road test pavements as shown in Figure (2) and (3). Only one set of values for the modulus of asphalt layer ($E_1=1035.5$ MPa), the base layer ($E_2=103.5$ MPa), and the sub-grade modulus ($E_3=51.7$ MPa) was taken from the original AASHTO road test because it is similar to the modulus values of local materials in practice ⁽⁸⁾. AASHTO Poisson's ratios of 0.4 for asphalt layer, 0.35 for base layer, and 0.4 for sub-grade layer were taken for the purpose of this analysis.

3-2-1 AASHTO equivalency factors of M1A1 tank load

Figure (6), Figure (7), and Figure (8) were prepared to show the calculated tensile strains in the direction of x, y, and r at the bottom fiber of asphalt concrete layer respectively under the M1A1 tank load. These calculated strains were for the AASHTO pavement structure shown in Figure (3) and for the simulation type 1 shown in Figure (4) above for the layout of M1A1 tank load. These strains were obtained for 400 calculating points for each one of these Figures using KENLAYER computer program ⁽¹¹⁾.

Figure (9) was prepared to show the calculated vertical compressive strains on the surface of sub-grade layer of AASHTO pavement structure shown in Figure (3) under M1A1 tank load. These strains were obtained for 400 calculating points using KENLAYER computer program ⁽¹¹⁾.

It was found that the calculated vertical compressive strains on the surface of sub-grade layer under M1A1 tank load are much more conservative than calculated tensile strains in the direction of x, y, and r at the bottom fiber of asphalt concrete layer in comparison with their similar type of strains reported by AASHTO ⁽¹⁰⁾, as shown in Figures (6) to (9). Therefore, the rutting criterion governed and was used to calculate the AASHTO equivalency factors of M1A1 tank load.

The maximum calculated vertical compressive strains on the surface of sub-grade layer under M1A1 tank load for the AASHTO ⁽¹⁰⁾ pavement structures are summarized in Table (2). The AASHTO ⁽¹⁰⁾ reported maximum vertical compressive strains on the surface of sub-grade layer for the AASHTO pavement structures under the standard 18 kips (80 kN) are shown also in Table (2). The values for the constant c of equation (1) for each one of AASHTO ⁽¹⁰⁾ pavement structures were obtained from Van Til et. al. ⁽⁹⁾. The AASHTO equivalency factors of M1A1 tank load were calculated using equation (1) are shown in Table (2).

3-2-1-1 Effect of M1A1 tank track width on AASHTO equivalency factors

The maximum vertical compressive strains on the surface of sub-grade layer under M1A1 tank load for the AASHTO ⁽¹⁰⁾ pavement structures were recalculated using type 2 layout for the simulation of shown in Figure (4) above and for the pavement structure shown in Figure (3) above.

This recalculation was carried out to investigate the effect of the track width on the AASHTO equivalency factors. Table (3) was prepared to show the AASHTO equivalency factors of M1A1 tank load based on the same variables used in preparing Table (2) but with the use of type 2 layout for the simulation of M1A1 tank load.

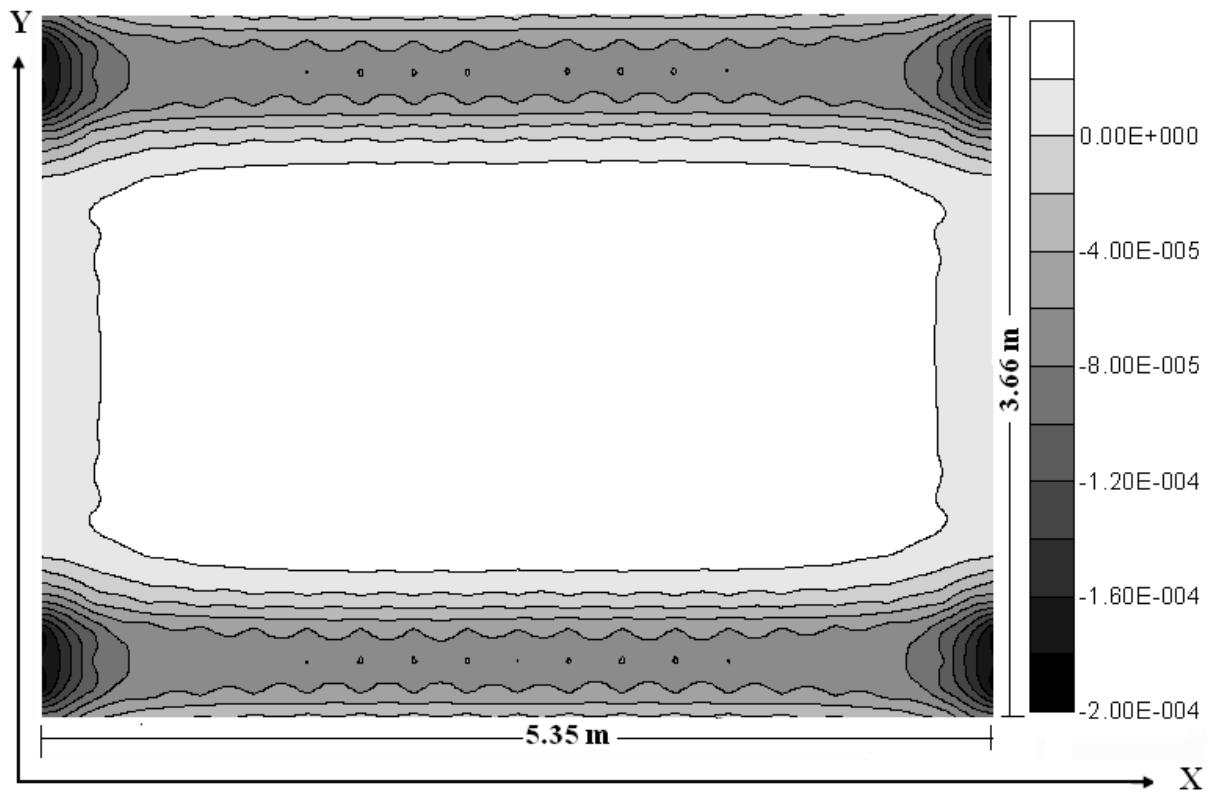


Figure (6): Tensile strain in the x direction (ϵ_x) at the bottom fiber of asphalt layer ($t_1=7.6$ cm and $t_2=56.6$ cm).

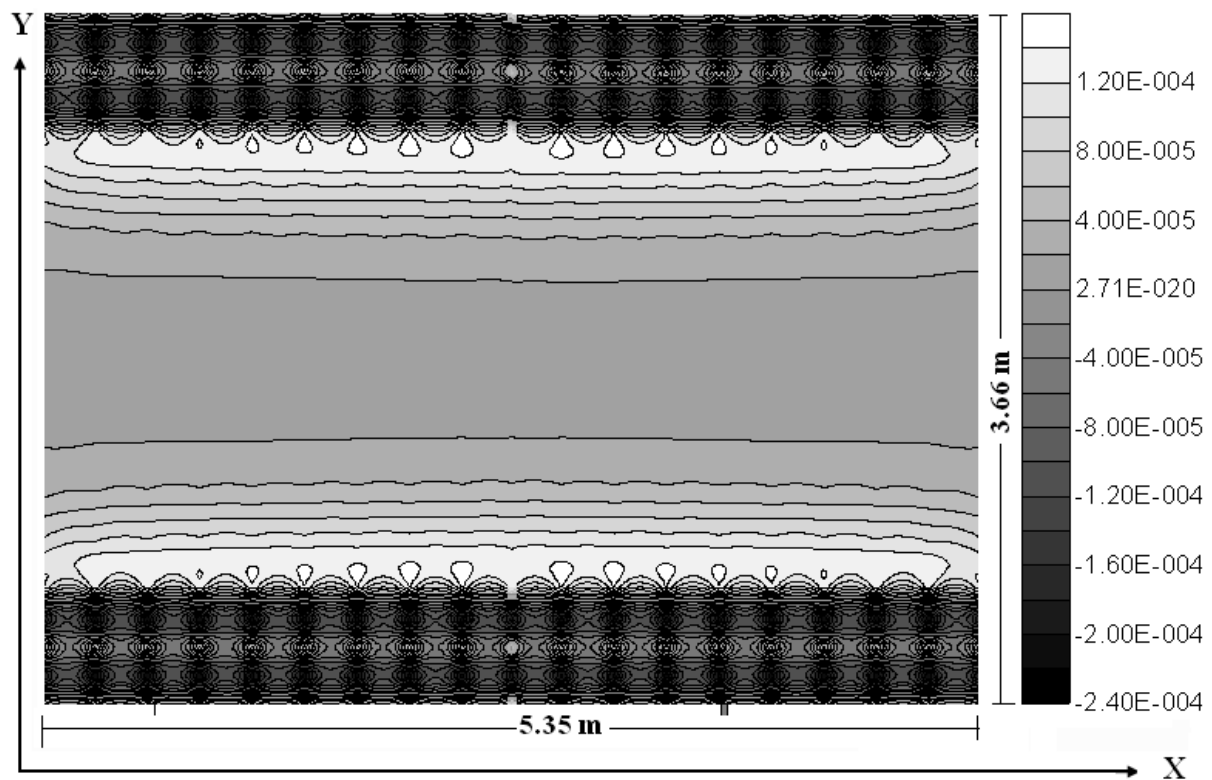


Figure (7): Tensile strain in the y direction (ϵ_y) at the bottom fiber of asphalt layer ($t_1=7.6$ cm and $t_2=56.6$ cm).

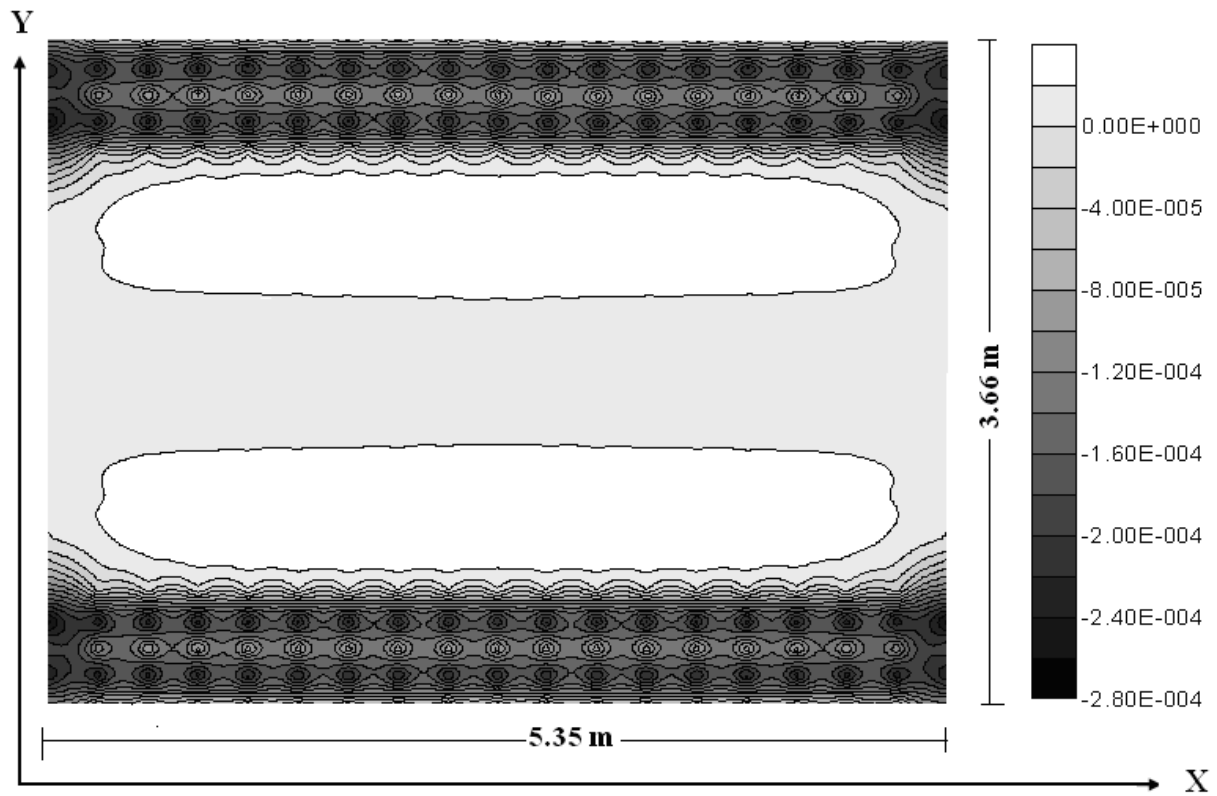


Figure (8): Horizontal principal tensile strain at the bottom of asphalt layer (ϵ_r) ($t_1=7.6$ cm and $t_2=56.6$ cm).

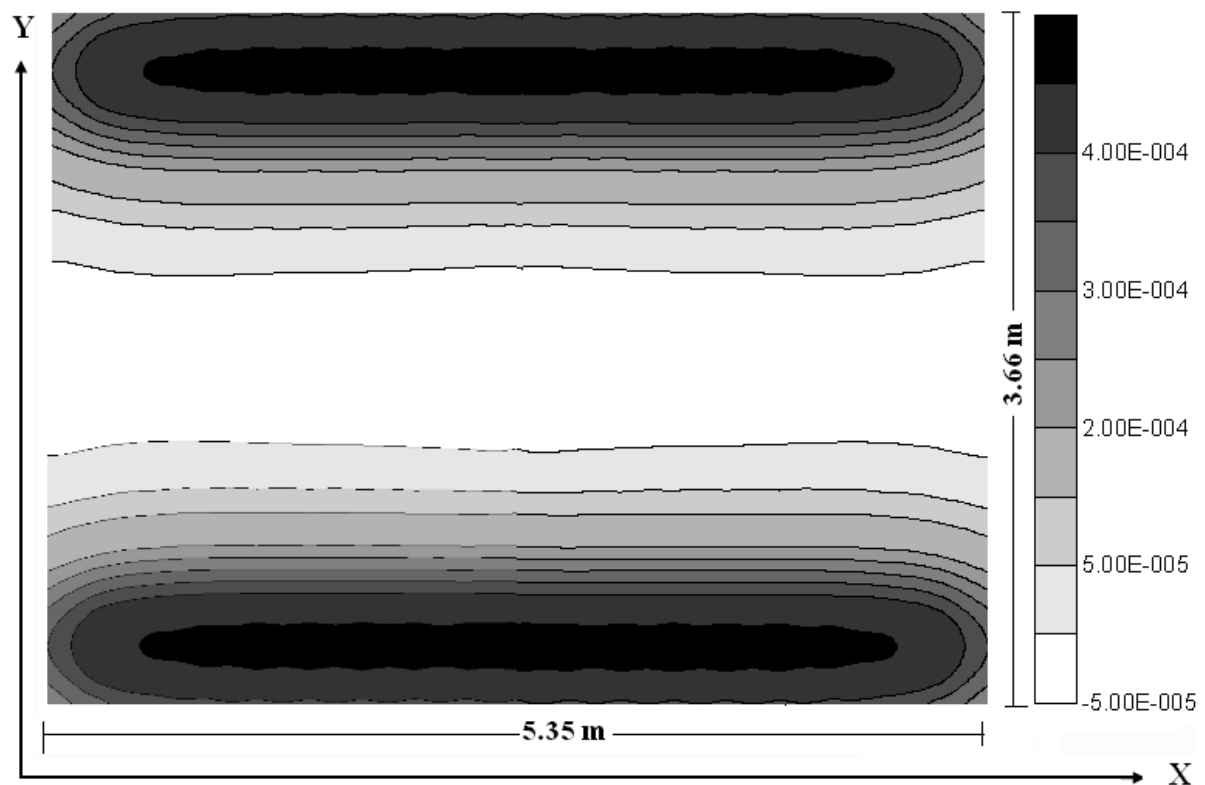


Figure (9): Vertical strain in the z direction (ϵ_z) on the surface of sub-grade layer ($t_1=7.6$ cm and $t_2=56.6$ cm).

Table (2): AASHTO equivalency factors of M1A1 tank using rutting criterion and for tank load simulation type 1(Figure (4)).

Modulus Layer 1 = 1035.5 MPa, $\mu_1 = 0.40$						
Modulus Layer 2 = 103.5 MPa, $\mu_2 = 0.35$						
Modulus Layer 3 = 51.724 MPa, $\mu_3 = 0.40$						
Thickness Layer 1 cm	Thickness Layer 2 cm	Source of Data	Vertical strain (ϵ_z) on sub-grade	SN	c	M1A1 Tank AASHTO Equivalency Factor
7.62	56.64	AASHTO ⁽¹⁾	0.0004330	4	3.54	1.438
7.62	56.64	Calculated ⁽²⁾	0.0005320	4	3.54	1.438
10.16	47.50	AASHTO ⁽¹⁾	0.0005280	4	3.43	1.300
10.16	47.50	Calculated ⁽²⁾	0.0005700	4	3.43	1.300
12.70	59.18	AASHTO ⁽¹⁾	0.0003420	5	3.43	3.240
12.70	59.18	Calculated ⁽²⁾	0.0004820	5	3.43	3.240
15.24	50.04	AASHTO ⁽¹⁾	0.0003740	5	3.43	7.650
15.24	50.04	Calculated ⁽²⁾	0.0006770	5	3.43	7.650
20.32	52.58	AASHTO ⁽¹⁾	0.0002940	6	4.29	19.40
20.32	52.58	Calculated ⁽²⁾	0.0005870	6	4.29	19.40

⁽¹⁾ AASHTO ⁽¹⁰⁾ maximum vertical strain (ϵ_z) on the sub-grade surface under the standard 18 kips (80 kN) axle load for terminal of serviceability (Pt) of 2.0.

⁽²⁾ Calculated maximum vertical strain (ϵ_z) on the sub-grade surface under the Abrams M1A1 military tank for type 1 simulated layout of tank loads shown in Figure (4) above.

Table (3): AASHTO equivalency factors of M1A1 tank using rutting criterion and for tank load simulation type 2(Figure (4)).

Modulus Layer 1 = 1035.5 MPa, $\mu_1 = 0.40$						
Modulus Layer 2 = 103.5 MPa, $\mu_2 = 0.35$						
Modulus Layer 3 = 51.7 MPa, $\mu_3 = 0.40$						
Thickness Layer 1 cm	Thickness Layer 2 cm	Source of Data	Vertical strain (ϵ_z) on sub-grade	SN	c	M1A1 Tank AASHTO Equivalency Factor
7.62	56.64	AASHTO ⁽¹⁾	0.0004330	4	3.54	3.890
7.62	56.64	Calculated ⁽²⁾	0.0006400	4	3.54	3.890
10.16	47.50	AASHTO ⁽¹⁾	0.0005280	4	3.43	2.4200
10.16	47.50	Calculated ⁽²⁾	0.0006830	4	3.43	2.4200
12.70	59.18	AASHTO ⁽¹⁾	0.0003420	5	3.43	3.2400
12.70	59.18	Calculated ⁽²⁾	0.0005580	5	3.43	3.2400
15.24	50.04	AASHTO ⁽¹⁾	0.0003740	5	3.43	5.3600
15.24	50.04	Calculated ⁽²⁾	0.0006080	5	3.43	5.3600
20.32	52.58	AASHTO ⁽¹⁾	0.0002940	6	4.29	12.0000
20.32	52.58	Calculated ⁽²⁾	0.0005250	6	4.29	12.0000

⁽¹⁾ AASHTO ⁽¹⁰⁾ maximum vertical strain (ϵ_z) on the sub-grade surface under the standard 18 kips (80 kN) axle load for terminal of serviceability (Pt) of 2.0.

⁽²⁾ Calculated maximum vertical strain (ϵ_z) on the sub-grade surface under the Abrams M1A1 military tank for type 2 simulated layout of tank loads shown in Figure (4) above.

3-2-2 AASHTO equivalency factors of M113A3 armoured vehicle load

The same procedure mentioned in paragraph 3-2-1 above to determine the AASHTO equivalency factors of M1A1 tank load was repeated to determine the AASHTO equivalency factors of M113A3 armored vehicle except that the dimensions and weight of M113A3 armored vehicle were used instead of the dimensions and weight of M1A1 tank. Also, the effect of track width of M113A3 armoured vehicle on AASHTO equivalency factors was studied.

Table (4) and Table (5) were prepared following the same procedure in preparing Table (2) and Table (3) to show the AASHTO equivalency factors of M113A3 armored vehicle load. Also, the rutting criterion governed and was used to calculate the AASHTO equivalency factors of M113A3 armored vehicle load. The maximum calculated vertical compressive strains on the surface of sub-grade layer under M113A3 armored vehicle load for the AASHTO⁽¹⁰⁾ pavement structures are summarized in Table (4) and Table (5).

Table (4): AASHTO equivalency factors of M113A3 armored vehicle using rutting criterion and for load simulation type 1 (Figure (5)).

Modulus Layer 1 = 1035.5 MPa, $\mu_1 = 0.40$						
Modulus Layer 2 = 103.5 MPa, $\mu_2 = 0.35$						
Modulus Layer 3 = 51.724 MPa, $\mu_3 = 0.40$						
Thickness Layer 1 cm	Thickness Layer 2 cm	Source of Data	Vertical strain (ϵ_z) on sub-grade	SN	c	M113A3 AASHTO Equivalency Factor
7.62	56.64	AASHTO ⁽¹⁾	0.0004330	4	3.54	0.060
7.62	56.64	Calculated ⁽²⁾	0.0001950	4	3.54	0.060
10.16	47.50	AASHTO ⁽¹⁾	0.0005280	4	3.43	0.040
10.16	47.50	Calculated ⁽²⁾	0.0002070	4	3.43	0.040
12.70	59.18	AASHTO ⁽¹⁾	0.0003420	5	3.43	0.115
12.70	59.18	Calculated ⁽²⁾	0.0001820	5	3.43	0.115
15.24	50.04	AASHTO ⁽¹⁾	0.0003740	5	3.43	0.070
15.24	50.04	Calculated ⁽²⁾	0.0001730	5	3.43	0.070
20.32	52.58	AASHTO ⁽¹⁾	0.0002940	6	4.29	0.040
20.32	52.58	Calculated ⁽²⁾	0.0001730	6	4.29	0.040

⁽¹⁾ AASHTO⁽¹⁰⁾ maximum vertical strain (ϵ_z) on the sub-grade surface under the standard 18 kips (80 kN) axle load for terminal of serviceability (Pt) of 2.0.

⁽²⁾ Calculated maximum vertical strain (ϵ_z) on the sub-grade surface under the armored vehicle for type 1 simulated layout of M113A3 loads shown in Figure (5)

Table (5): AASHTO equivalency factors of M113A3 armoured vehicle using on rutting criterion and for M113A3 load simulation type 2 (Figure (5)).

Modulus Layer 1 = 1035.5 MPa, $\mu_1 = 0.40$						
Modulus Layer 2 = 103.5 MPa, $\mu_2 = 0.35$						
Modulus Layer 3 = 51.7 MPa, $\mu_3 = 0.40$						
Thickness Layer 1 cm	Thickness Layer 2 cm	Source of Data	Vertical strain (ϵ_z) on sub-grade	SN	c	M113A3 AASHTO Equivalency Factor
7.62	56.64	AASHTO ⁽¹⁾	0.0004330	4	3.54	0.02
7.62	56.64	Calculated ⁽²⁾	0.0001420	4	3.54	0.02
10.16	47.50	AASHTO ⁽¹⁾	0.0005280	4	3.43	0.016
10.16	47.50	Calculated ⁽²⁾	0.0001570	4	3.43	0.016
12.70	59.18	AASHTO ⁽¹⁾	0.0003420	5	3.43	0.040
12.70	59.18	Calculated ⁽²⁾	0.0001320	5	3.43	0.040
15.24	50.04	AASHTO ⁽¹⁾	0.0003740	5	3.43	0.034
15.24	50.04	Calculated ⁽²⁾	0.0001400	5	3.43	0.034
20.32	52.58	AASHTO ⁽¹⁾	0.0002940	6	4.29	0.030
20.32	52.58	Calculated ⁽²⁾	0.0001270	6	4.29	0.030

⁽¹⁾ AASHTO ⁽¹⁰⁾ maximum vertical strain (ϵ_z) on the sub-grade surface under the standard 18 kips (80 kN) axle load for terminal of serviceability (Pt) of 2.0.

⁽²⁾ Calculated maximum vertical strain (ϵ_z) on the sub-grade surface under the M113A3 military armoured vehicle for type 2 simulated layout of M113A3 loads shown in Figure (5) above.

3-3 Damaging effect of tracked armoured vehicles on the surface.

Besides the structural damaging effect of tracked armoured vehicle loads on flexible pavement structures in terms of rutting and fatigue cracking, there is another damaging effect on the functional properties of the surface of the asphalt concrete layers i.e. the permanent deformations in the three directions and distress due to the movement of the rigid track chain on the relatively softer asphalt layer surface. Figure (10) to Figure (12) were prepared to show the strains in the direction of x, y, and z at the surface of asphalt layer respectively under M1A1 tank load on AASHTO pavement structure shown in Figure (3) using type 1 load simulation shown in Figure (4) above.

Figure (13) was prepared to show shear strain in the direction of (xy) at the surface of asphalt layer under M1A1 tank load on AASHTO pavement structure shown in Figure (3) using type 1 load simulation shown in Figure (4). Table (6) was prepared to compare the displacements at the surface of asphalt layer under M1A1 tank with that reported by AASHTO ⁽¹⁰⁾ 18 kips (80 kN) standard axle load on the same original AASHTO road test pavements.

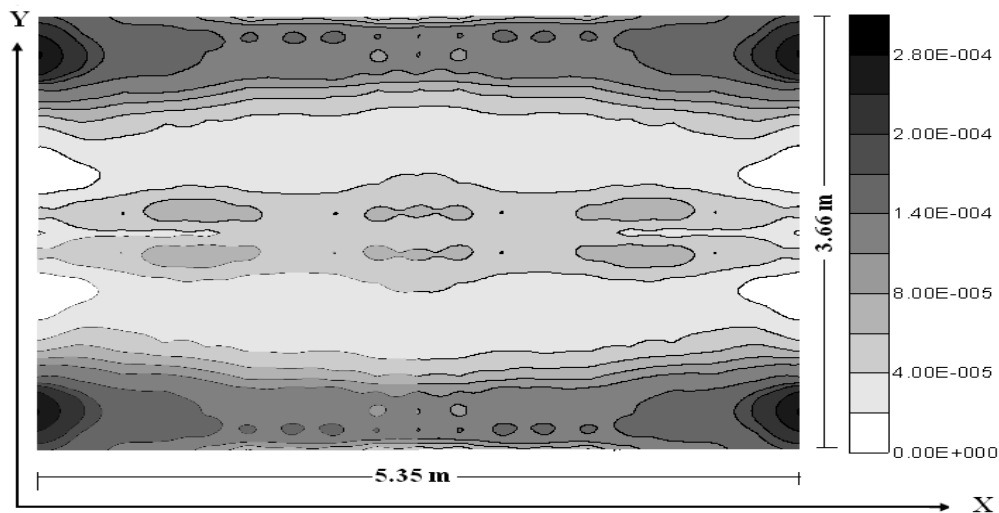


Figure (10): Strains in the x direction at the surface of asphalt layer under the tracked armoured vehicle loads for the pavement structure shown in Figure (5), ($t_1=7.6$ cm and $t_2=56.6$ cm).

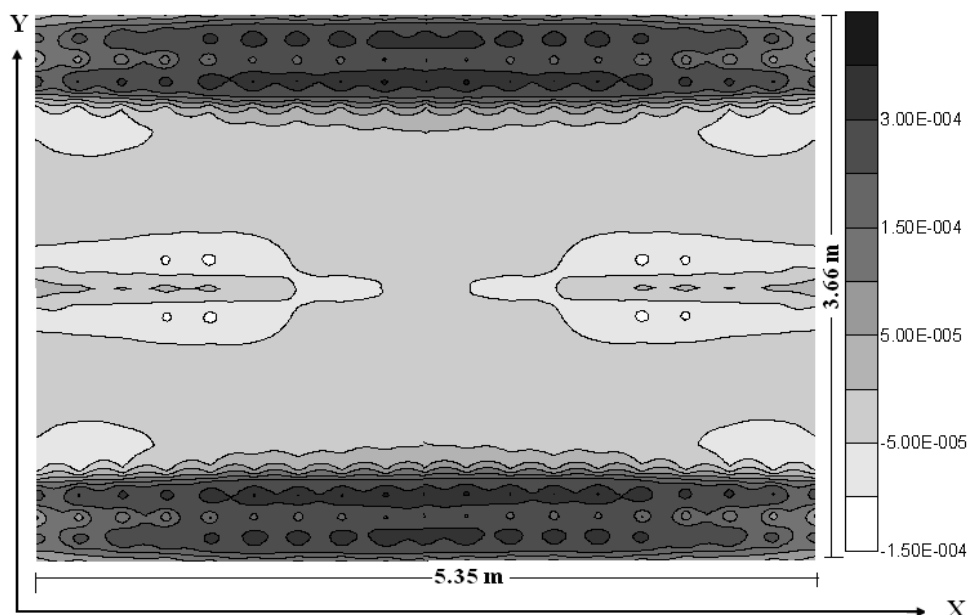


Figure (11): Strains in the y direction at the surface of asphalt layer under the tracked armoured vehicle loads for the pavement structure shown in Figure (5), ($t_1=7.6$ cm and $t_2=56.6$ cm).

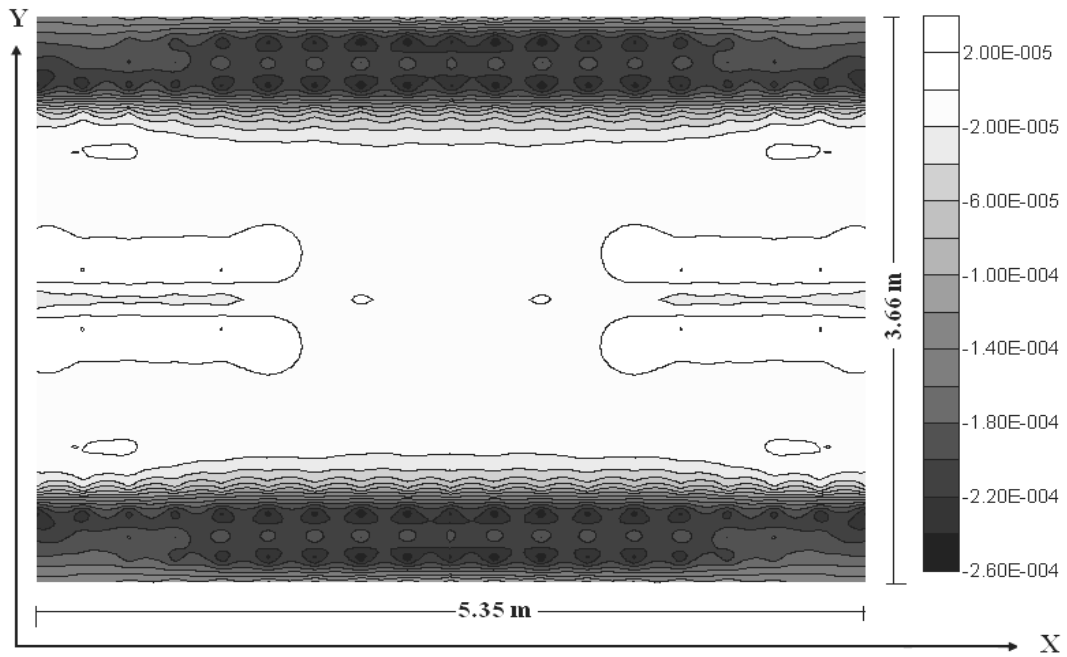


Figure (12): Strains in the z direction at the surface of asphalt layer under the tracked armoured vehicle loads for the pavement structure shown in Figure (5), ($t_1=7.6$ cm and $t_2=56.6$ cm).

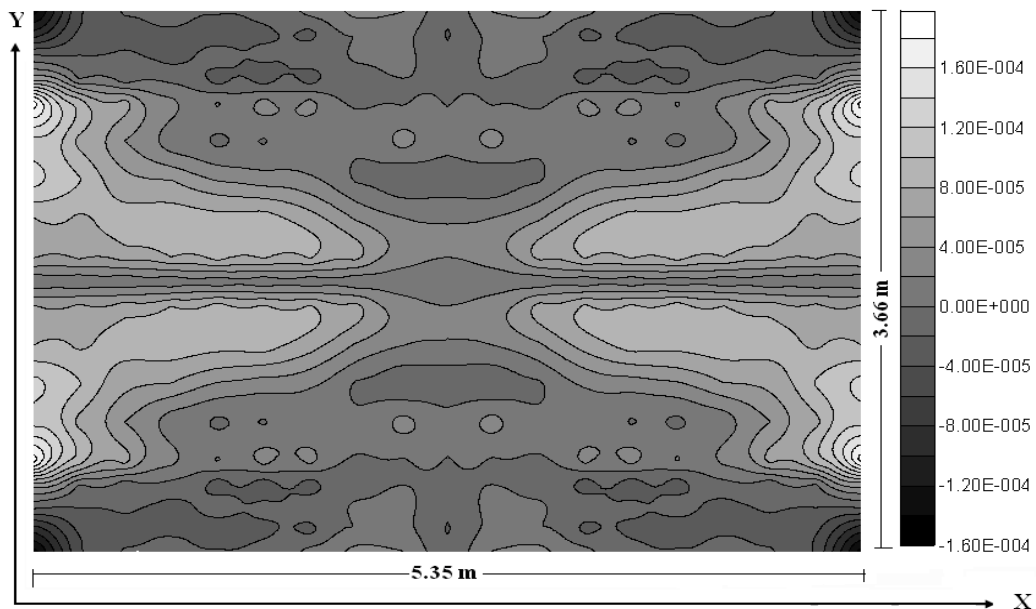


Figure (13): Shear strain in the xy direction at the surface of asphalt layer under the tracked armoured vehicle loads for the pavement structure shown in Figure (5), ($t_1=7.6$ cm and $t_2=56.6$ cm).

Table (6): Maximum displacements at the surface of asphalt layer under AASHTO 18 kips and M1A1 tank.

Modulus Layer 1 = 1035.5 MPa, $\mu_1 = 0.40$				
Modulus Layer 2 = 103.5 MPa, $\mu_2 = 0.35$				
Modulus Layer 3 = 51.7 MPa, $\mu_3 = 0.40$				
Thickness Layer 2 cm	Thickness Layer 2 cm	Load Type	Deformation Type	Deformation Value mm)(
7.62	56.64	18 kips	displacement x	0.075946
7.62	56.64	Tank	displacement x	0.137414
7.62	56.64	18 kips	displacement y	0.073406
7.62	56.64	Tank	displacement y	0.141732
7.62	56.64	18 kips	displacement z	0.101346
7.62	56.64	Tank	displacement z	2.616200

4- Discussion of results and Conclusions

It was found that military tracked armoured vehicles have a pronounced damaging effect on flexible pavements in terms of AASHTO equivalency factors as follows:

- 1- The AASHTO equivalency factors of M1A1 tank load were found to be from 1.3 to 19.4 based on rutting criterion. Increasing the thickness of the asphalt layer pavement increases the AASHTO equivalency factors of M1A1 tank load. This means that the structural damaging effect of M1A1 tank load on flexible pavements of major highways and main principal roads is much more than its damaging effect on the flexible pavement of local and secondary roads. It was found that increasing the width of track or the layout of M1A1 tank loads has a small effect from the theoretical point of view due to the high magnitude of the M1A1 tank load. Practically speaking, AASHTO equivalency factors of M1A1 tank load calculated using type 1 M1A1 tank loads layout are more accurate than those calculated using type 2 loads layout because the track (contact area) is not in full contact with the surface of paved roads as shown in Figure (1). It was found also, that M1A1 tank load has a severe damaging effect on the functional serviceability of surface of asphalt layer in terms of deformation and strains due to the effect of relatively rigid track chain in comparison of asphalt surface.

2- The AASHTO equivalency factors of M113A3 armored vehicle load were found to be from 0.016 to 0.115 based on rutting criterion. Increasing the thickness of the asphalt layer pavement increases the AASHTO equivalency factors of M113A3 armored vehicle load. This means that the structural damaging effect of M113A3 armored vehicle load on flexible pavements of major highways and main principal roads is much more than its damaging effect on the flexible pavement of local and secondary roads. M113A3 armored vehicle load has a severe damaging effect on the functional serviceability of surface of asphalt layer in terms of deformation and strains due to the effect of relatively rigid track chain..

6- Recommendations

Based on the results of this study, an economic evaluation for the cost of damage that had been caused by the frequent movement of military tracked armoured vehicles on the national road network during the last six years is required. Another study is necessary to determine the damaging effect of military tracked armoured vehicles on the national road network during summer seasons.

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