INTERNATIONAL RESEARCH JOURNAL OF HUMANITIES AND INTERDISCIPLINARY STUDIES
(Peer-reviewed, Refereed, Indexed & Open Access Journal)
DOI : 03.2021-11278686 ISSN : 2582-8568 IMPACT FACTOR : 5.71 (SJIF 2021)

Comparative Numerical Consider of Proposed Multi-layer Composites beneath Affect Stacking

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DOI No. 03.2021-11278686 DOI Link :: https://doi-ds.org/doilink/06.2021-36521532/IRJHISMC210515

Abstract:

Airport runway pavement is generally subjected to multi levels of impact loadings due to the hard landing of exceptionally large and heavy weighted aircrafts and can be subjected to high velocity and heavy weighted falling objects during accidents, terrorist attacks etc. As a consequence, surface depression, rutting and potholes are often visible for heavily serviced runway pavements or severe damage after accidents. It is therefore, necessary to evaluate the impact resistance of the conventional runway pavements and develop new multi-layer composite and concrete runway pavements to increase the resistance to impact load. The FE model was well validated through drop-weight impact test results to successfully model the dynamic response of runway pavement under impact loading. The numerical study further confirmed the improved impact resistance of the proposed multi-layer composite to resist impact loads. Furthermore, large scale FE model was developed to simulate the runway pavement and aircraft interaction under moving and impact loading. Based on the developed 3D model, parametric studies were carried out initially on the small scale model and then, on large scale model to identify the key parameters affecting the runway resistance to impact loads.

Keywords: *Multi-layer composite runway pavement, impact load, moving load, impact resistance, finite element analysis*

INTRODUCTION:

This chapter firstly develops a finite element (FE) model to simulate multi-layer composite under impact load and then validates the FE model using results from literature. The drop weight test results carried out on typical concrete and flexible pavement by Wu (2012) were used for validation. Furthermore, the validated FE model of flexible pavement was used to compare the impact resistance of some selected multi-layer composites. In addition, parametric study was conducted to evaluate the effect of different parameters in influencing the impact resistance of the validated FE models.

CONCRETE PAVEMENT SPECIMEN UNDER IMPACT LOADING

In this study, a 3D FE model was developed in ABAQUS/Explicit to validate the model with the test results of impact test conducted by Wu (2012). The model was composed of 275 mm thick concrete slab over subgrade. The subgrade was 600 mm thick and composed of sand. The concrete specimen was 900 mm × 900 mm in dimension and the dimension of the underneath subgrade was 1m × 1 m (Figure 1). To resist the uplift of the two parallel sides of the concrete slab, two textile belts were used near the edges over top surface of concrete slab. Hemispherical drop mass was used to apply the impact load at the mid-point of the top surface of concrete slab. The diameter of the drop mass was 100 mm and the length of the drop mass was 1.292 m. The impact velocity applied by the drop mass was 5.133 m/s. The material properties used in the analysis of FE model is given in Tables 1- 3.

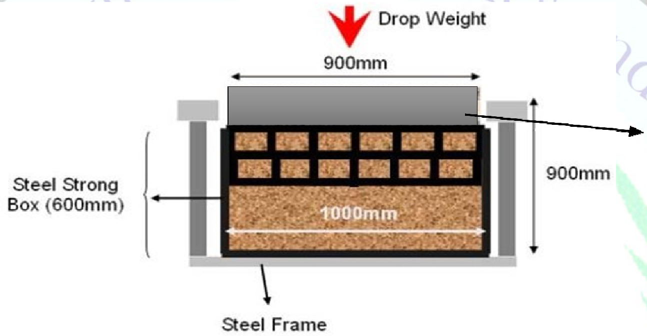

Figure1: Experimental set up of concrete pavement specimen (Wu, 2012)

Parameters	Value
Young's modulus, E (GPa)	33
Poisson's ratio, υ	0.2
Density, ρ (Kg/m³)	2400
Compressive strength, f_c (MPa)	54
Tensile strength, f_t (MPa)	2.7

Table 1: Mechanical properties of concrete slab

Parameters	Geocell reinforced sand	Sand
Young's modulus, E (MPa)	103.5	40
Poisson's ratio, υ	0.3	0.3
Density, ρ (Kg/m³)	1600	1600
Friction angle, β	40°	40°
Cohesion, c (KPa)	89	13.8

Table 2: Mechanical properties of sub grade

Parameters	Impactor	Textile belt
Young's modulus, E (GPa)	207	2.1
Poisson's ratio, υ	0.3	0.3
Density, ρ (Kg/m³)	118000	1000
Yield strength, f_y (MPa)	500	80
Tangent modulus	-	39000
Erosion strain	-	0.006

Table 3: Mechanical properties of drop mass/impactor and textile belt

ELEMENT SELECTION AND MATERIAL MODELLING

a) Concrete slab

The concrete slab was modelled with 8-node linear brick elements (C3D8R) with reduced integration and hourglass control. Concrete damage plasticity model available in ABAQUS/Explicit was used to simulate the elasto-plastic behaviour of concrete slab. The properties used for concrete slab are given in Table 1

b) Sub grade

The subgrade was also modelled with 8-node linear brick elements (C3D8R) with reduced integration and hourglass control. The elasto-plastic behaviour of subgrade soil was simulated by using Drucker-Prager plasticity model. The properties used for geocell reinforced and normal subgrade sand is given in Table 2

c) Impactor/Drop mass and Textile belt

The impactor was modelled by using 10-node modified second order elements (C3D10M) with reduced integration and hourglass control due to greater stiffness of the element and also to adjust with the shape of the hemispherical head of the impactor. The mechanical properties of impactor were used as given in Wu (2012). Textile belt was included in FE model on the edge of top surface of concrete as described in experimental set up of Wu (2012). Textile belts were defined with 4-node quadrilateral membrane elements (M3D4R) with reduced integration and hourglass control. The plastic-kinematic model was also adopted to simulate the bi-linear behaviour of textile belt. The plastic option of ABAQUS/6.13-3 was selected and kinematic hardening was used to implement the plastic-kinematic model of textile belt. The detail properties of cylindrical shaped hemispherical impactor and textile belt as used by Wu (2012) are given in Table 3. The plastic properties were collected from Carvelli et al. (2007).

d) FE meshing and contact modeling

The selection of proper mesh size of FE model was important for accurate analysis results and more importantly for high strain loading. For overall model, small mesh size was selected for better result. Comparatively finer mesh size was selected for concrete slab compared to the subgrade since concrete slab was directly subjected to impact load. The mesh size of 5 mm was adopted for concrete slab and 8 mm adopted for subgrade based on convergence study. The mesh size selected for the textile belt was 10 mm. Figure 2 shows the FE meshing distinctly. General contact algorithm was used to define the interaction of hemispherical impactor and concrete pavement specimen. The contact surfaces of concrete slab and subgrade was tied up and surface to surface interaction was defined between concrete slab and subgrade. Hard contact formula was used to define normal stress behaviour and penalty frictional formulation was used to define tangential stress behaviour at contact surfaces for both general and surface to surface contact approach. Similar modelling strategy was also adopted for the interaction of textile belt and concrete slab. However, dynamic friction co-efficient value of 0.45 was used at interaction of adjacent surfaces since under impact loading the usual friction co- efficient remain within 0.4-0.55 (Wu et al., 2012).The symmetric FE model of concrete pavement specimen is illustrated in Figure 3.

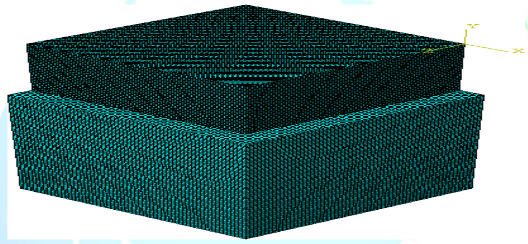

Figure 2: FE meshing of concrete pavement specimen

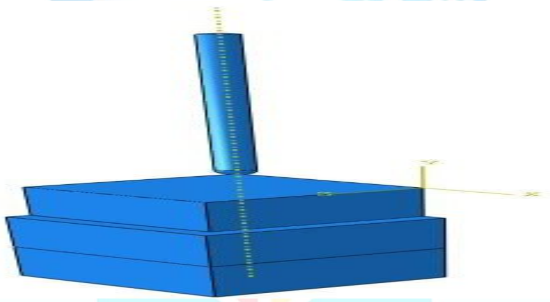

Figure 3: Symmetric FE model of the concrete pavement specimen

e) Boundary conditions and loadings

The fixed support condition was applied on two sides and the bottom of the sand. Symmetric support condition was provided on other two sides of sand and also on two sides of concrete pavement specimen. The other two sides of concrete pavement specimens were not restrained. Two vertical faces of the quarter of drop mass or impactor were also provided symmetric boundary condition. The other vertical sides of the impactor were restrained against lateral movement. The total surface of the impactor was assigned an impact velocity of 5.133 m/s to simulate the real test condition. The impact velocity was applied by using predefined velocity option which was available in ABAQUS/Explicit.

VALIDATION OF FE MODEL

The results obtained from established FE model of concrete pavement specimen were compared with the test results of drop weight impact tests performed by Wu (2012). In Wu (2012), the maximum vertical deflections were determined at three specific points on the top surface of the concrete pavement specimen as shown in Figure 4.

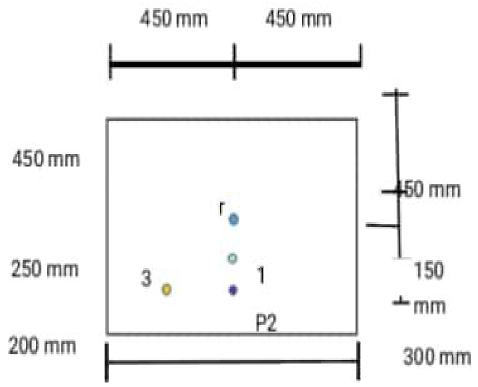

Figure 4: Selected locations to measure deflections by Wu (2012)

Location	Maximum Deflection in FE analysis (mm)	Maximum Deflection in experimental investigation of Wu (2012) (mm)	FE result/experimental result	Coefficient of variation (COV)
P1	26.34	26.07	1.01	0.007
P2	24.6	27.06	0.91	0.067
P3	25.32	27.98	0.9	0.070

Table 4: Maximum deflections of concrete slab under impact load

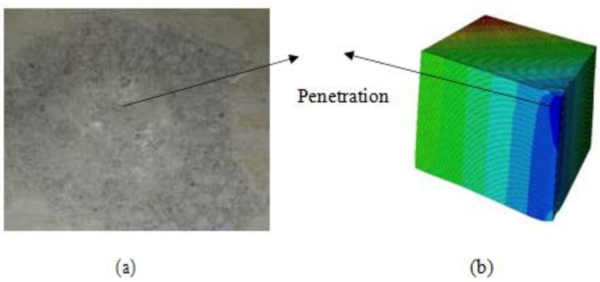

Figure 5: Failure mode of concrete pavement specimen (a) Impact test of Wu (2012) (b) FE analysis

In the FE analysis, failure of concrete slab was governed by penetration at the region of the application of impact loading which was found same as noted from the experimental test of Wu (2012). Figure 5 shows the failure modes of the concrete pavement from FE analysis and impact test of Wu (2012).

COMPARATIVE STUDY ON MULTI-LAYER COMPOSITES UNDER IMPACT LOADING

To improve the performance of runway pavement under impact loading, two types of multi-layer composite runway pavement were proposed. Comparative study was conducted on conventional type of runway pavement generally used in India and the two proposed multi-layer composites to identify the impact resistant multi-layer composite. Higher rigid materials were introduced in the proposed multi-layer composites as research informed that rigid materials in composite specimen can efficiently counteract the dynamic loads acting on the structure (Wu, 2012). The modelling of the asphalt concrete surface layer under impact load was carried out according to the validated FE models as discussed in the previous sections. The Prony series data for asphalt concrete at 25-degree Celsius temperature was adopted from Modarres and Shabani (2015). The concrete like materials under impact loading were modelled by Concrete Damage Plasticity method which was previously validated in Ali et al. (2016).

Model Type		Model dimension(L × W × D) mm	Layer Thickness (mm)
Conventional	AC	900 × 900 × 375	75
	CTA		300
Type 1	AC	900 × 900 × 375	75
	HSC		175
	CTA		125
Type 2	AC	900 × 900 × 375	75
	HSC		175
	CM		125

Table 5: Geometrics of the conventional and proposed multi-layer composites

Property	AC	CTA	HSC	CM
Compressive strength, f_c(MPa)	4.7	5	54	10
Tensile strength, f_t(MPa)	_	0.5	3.25	0.08

Table 6: Mechanical properties of the materials

The subgrade part was not considered in the comparative analysis since the composition of the multi-layer composite runway pavement was the main concern. Table 5 and 6 shows the geometries and material properties of the three types of multi-layer composites.

In the conventional runway pavement of India, light cementitious material is used in the base and sub-base layer by using around six percent cement. The compressive strength of such cement treated aggregate was obtained from cylinder tests and used in the comparative study. Strain rate effect was incorporated into the material properties during the comparative analysis of the multi-layer composites. The points selected over the top surface layer of asphalt concrete for the comparative study is shown in Figure 6.

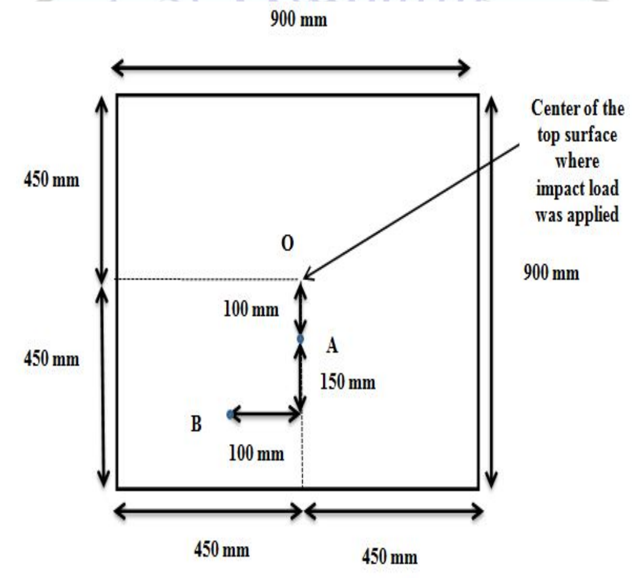

Figure 6: Selected locations on top of asphalt concrete surface layer for comparative study

The displacement histories of the comparative analysis for the specific three points are shown in Figures 7(a), (b) and (c). Figures 7(a), (b) and (c) shows that at all the selected locations, deflections can be reduced significantly by proposed multi-layer composites compared to the conventional composite. Table 7 shows the performance of the proposed multi-layer composites.

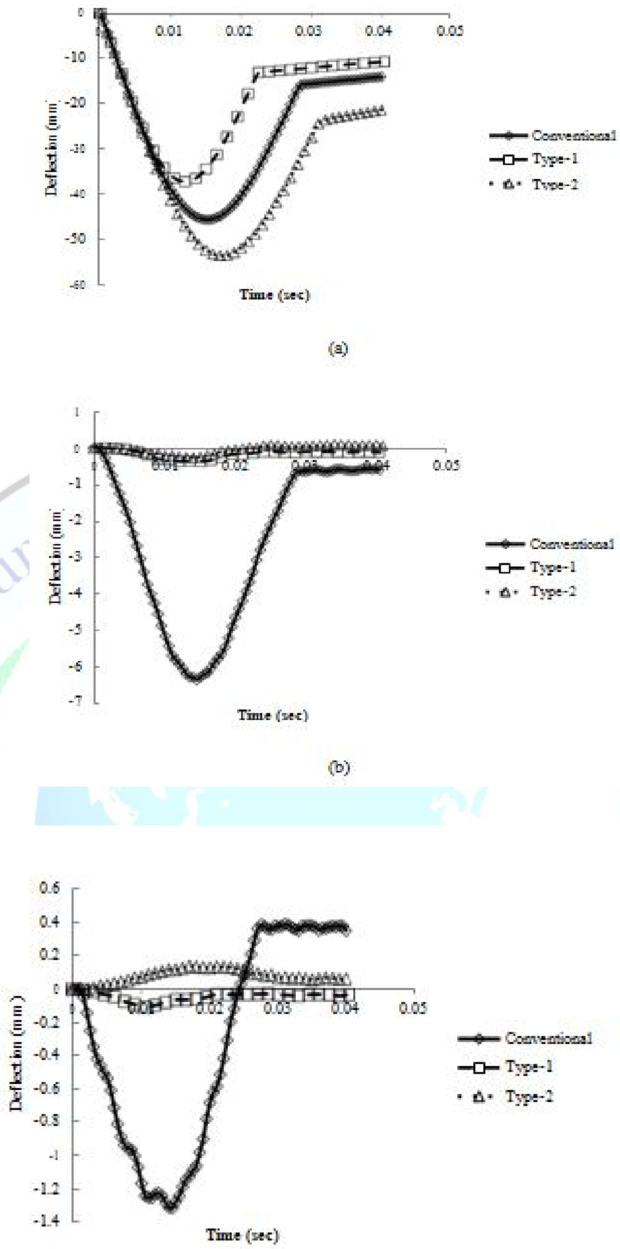

Figure 7: Deflection time history of multi-layer composites under impact loading (a) center (b) location A (c) location B

Location	Maximum Deflection (mm)			Maximum Deflection Ratio	
	Conventional	Type 1	Type 2	Type 1/Conventional	Type 2/Conventional
O	45.60	36.50	53.50	0.80	1.17
A	6.28	0.35	0.26	0.06	0.04
B	1.30	0.08	0.13(Uplift)	0.06	0.1

Table 7: Deflection of multi-layer composites under impact loading

Figure 7 shows that at all the selected points, deflection can be reduced significantly when using Type 1 multi-layer composite compared to the conventional composite. The maximum downward deflections at O, A and B points can be reduced by 25%, 95% and 94% with Type 1 multi-layer composite compared to the conventional composite under the specified loading condition. In case of Type 2 composite, the downward deflection was reduced by 96% at location A. However, Type 2 model showed higher deflection compared to the conventional composite at center of the top surface (location O). In addition, uplift was found at location B under the specified impact load. The comparative study also shows that using of rigid base instead of using light cementitious material like cement treated aggregate was quite significant in the reduction of deflection at the asphalt concrete surface layer. Therefore, composition similar to Type 1 can be used as an economical multi-layer composite runway pavement due to its improved impact resistance.

PARAMETRIC STUDIES ON FLEXIBLE PAVEMENT SPECIMEN

The parametric study was conducted to investigate a few key geometric and material parameters to determine the significance of these parameters in affecting the impact resistance of improved multi-layer composite (Type 1). These parameters include thickness of base and sub-base layer, compressive strength of base and sub-base layer, impact velocity of impactor and the mass density of the impactor.

a) Effects of base to sub-base thickness ratio

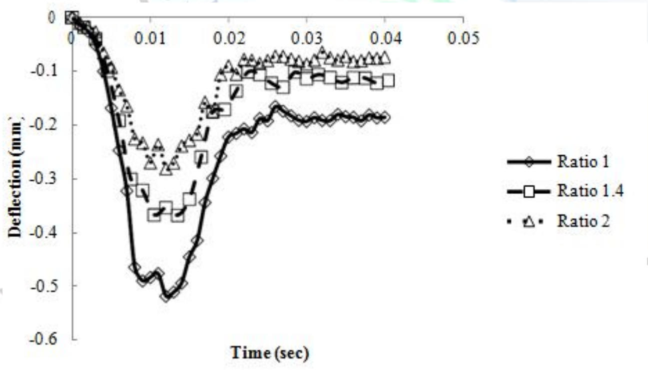

Figure 3.19: Effects of base to sub-base thickness ratio at location A

Figure 3.19 illustrates the variation of deflection at point A with the change of base to sub-base thickness ratio of the improved multi-layer composite. Figure 3.19 shows that under impact loading, the deflection at the surface layer of improved multi-layer composite reduces significantly with the increase of base to sub-base thickness ratio within the selected range. At impact velocity of 4.5 m/sec, deflection was reduced about 46% when the base to sub-base thickness ratio was increased from 1 to 2. Since, the base layer absorbs considerable amount of impact energy, so the increase of the thickness ratio with selecting recommended value of base and sub-base thickness will be helpful to increase the impact resistance the thereby to reduce the deflection.

b) Effects of compressive strength

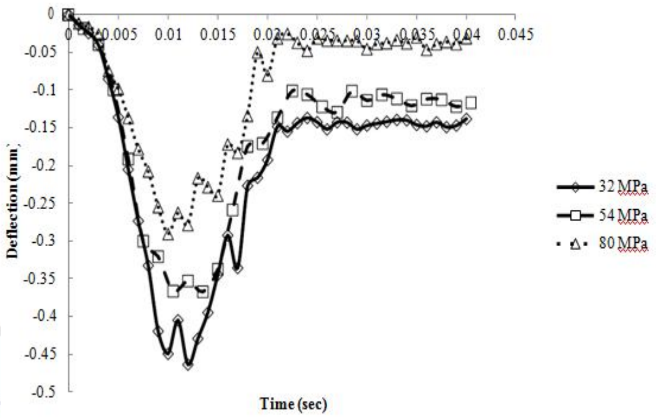

Figure 3.20: Effects of compressive strength of base layer at location A

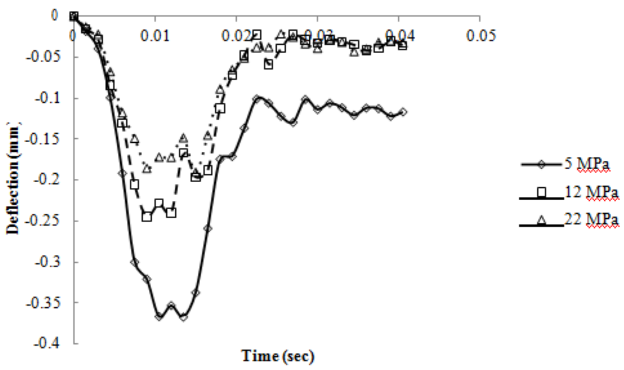

Figure 3.21: Effects of compressive strength of sub-base layer at location A

The effects of compressive strength of base and sub-base layer of the improved multi-layer composite in influencing the deflection under impact velocity of 4.5 m/sec were separately studied in this section. The change in deflection was noted at point A as shown in Figure 3.20. The compressive strengths for base layer were selected as 31 MPa, 54 MPa and 80 MPa whereas for sub-base layer the strengths were 5 MPa, 12 MPa and 22 MPa. Figures 3.20 and 3.21 show the variation of deflection at point A with the change of compressive strengths in base and sub-base layer of the improved multi-layer composite under impact loading. The deflection was found to reduce around 38% when the compressive strength of base layer was increased from 31 MPa to 80 MPa. In case of sub- base layer, deflection was found to reduce around 50% when the compressive strength of sub-base layer was increased from 5 MPa to 22 MPa.The result implies that the increase in the rigidity of the base and sub-base layer is beneficial in the decrease of deflection. Therefore, the use of high strength concrete and cement treated aggregate with high percentage cement can be used in the base and sub-base layer respectively to reduce the deflection as well to ensure an impact resistant multi-layer composite structure.

c) Effects of impact velocity

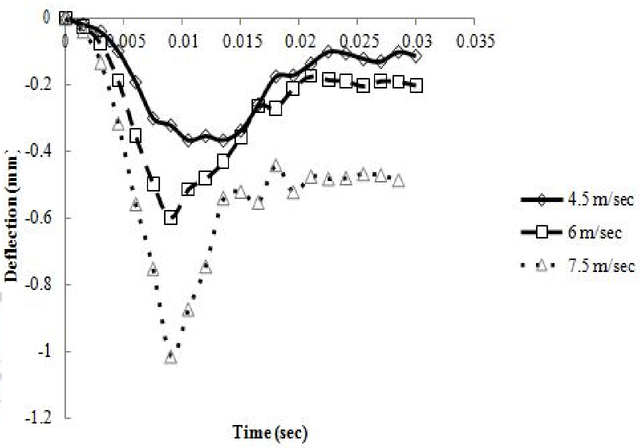

Figure 3.22: Effects of impact velocity on asphalt concrete surface layer at location A

The impact velocity of the impactor was varied from 4.5 m/sec to 12 m/sec for the improved multi-layer composite with constant impact mass density of 116447 kg/m³ to investigate the influence of impact velocity on the multi-layer composite. Figure 3.22 shows the variation of deflection of asphalt concrete at point A with different impact velocities. Figure 3.22 shows that the deflection of improved multi-layer composite increases significantly with the increase of impact velocity within the selected range. The deflection was found to increase around 64% when the impact velocity was increased from 4.5 m/sec to 12 m/sec.

d) Effects of mass density of impactor

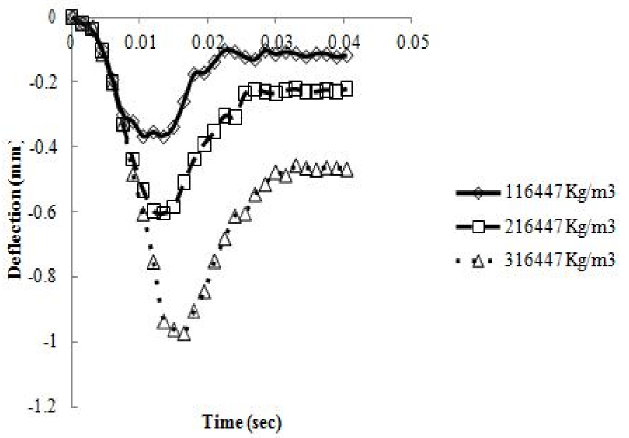

Figure 3.23: Effects of mass density of impactor on asphalt concrete surface at location A

The mass density of the impactor was varied from 116447 kg/m³ to 316447 kg/m³ on the Improved multi-layer composite with constant impact velocity of 4.5 m/sec to investigate the influence of mass density of impactor on the multi-layer composite. Figure 3.23 shows the variation of deflection of asphalt concrete at point A with three different mass densities of 116447 kg/m³, 216447 kg/m³ and 316447 kg/m³. Figure 3.23 shows that the deflection of improved multi-layer composite was increased significantly with the increase of impact mass density within the selected range. The deflection was found to increase around 63% when the mass density of impactor was increased from 116447 kg/m³ to 316447 kg/m³. However, the rate in the increase of deflection within the selected range of mass densities of the impactor was almost same.

CONCLUSIONS:

A 3D FE model was established using ABAQUS/Explicit and validated by existing experimental results to simulate behaviour of flexible pavement under drop weight impact. After validation, comparative analysis was carried out on the performance of conventional runway pavement composition and two proposed multi-layer composites under impact loading. Based on the study, the core findings of the study are summarized below:

The introduction of rigid base such as high strength concrete and cement treated aggregate was found effective in reducing deflection under impact loading.

The deflection of proposed composite was reduced significantly (maximum 95%) as high strength concrete was used in the base layer instead of cement treated aggregate. The introduction of cement mortar in sub-base was able to slightly improve the impact resistance of the proposed composite.

The increase of the base to sub-base thickness ratio under such test condition could significantly enhance the impact resistance of the improved multi-layer composite under impact loading. The deflection of the proposed composite was reduced about 46% when the base to sub-base thickness ratio was increased from 1 to 2.

Increase of compressive strength of base and sub-base layer within the selected range and under the test condition could significantly increase the impact resistance of the proposed multi-layer composite. The deflection was reduced by around 38% when the compressive strength of base layer was increased from 31 MPa to 80 MPa. And the deflection was reduced by around 50% when the compressive strength of sub-base layer was increased from 5 MPa to 22 MPa.

Impact resistance of the proposed multi-layer composite was reduced significantly with the increase of impact velocity within the selected range and under the drop weight impact test condition. The deflection was increased by around 64% when the impact velocity was increased from 4.5 m/sec to 12 m/sec.

Impact resistance of the proposed multi-layer composite was also decreased significantly with the increase of impact mass density within the selected range and under mentioned test condition. The deflection was increased by around 63% when the mass density of impactor was increased from 116447 kg/m³ to 316447 kg/m³.

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