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Numerical Simulation of Modified Rubberized Concrete Block Under Impact Loads

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Abstract: Rubberized Concrete was innovated by many researchers to enhance energy absorption under impact load and by reusing scrap tires. Thus, this research was aims to develop the numerical procedure using the Finite Element Method (FEM) to simulate modified rubberized concrete under impact loads and predict its energy absorption under different impact loads. Three existing constitutive models: Concrete Damage Plasticity (CDP), Drucker-Prager (DP), and Modified Drucker-Prager Cap (MDPC) available in ABAQUS software were used to replicate the rubberized concrete with 10% of Rice Hush Ash (RHA) as cement substitution and different percentages (0%, 5%, 10%, 15%, and 20%) of crumb rubber as sand replacement. All three models produced successful FEM results with reasonable modelling assumption, and the CDP model was more effective in simulating rubberized concrete under impact to predict energy absorption than DP and MDPC models. Further, it was concluded that crumb rubber could enhance the energy absorption of concrete. Generally, the energy absorption of the concrete increased as the crumb rubber increase. However, the strength decreased as the crumb rubber increased, but 10% of RHA in concrete mix can maintain the concrete strength. Overall, this study reveals that FEM incorporated with CDP model are able to predict the impact response of modified crumber rubber as an application of concrete road barrier.

Keywords: Impact Velocity, Rubberized Concrete, CDP, DP, MDPC

1. Introduction

Concrete, a human-made material that the most frequently used on the earth. Concrete is designed to withstand impact loads, but its energy absorption is not perfect for a structure requiring high energy absorption capacity. For example, a concrete road barrier with high capacity energy absorption can reduce or minimize impact force from uncontrolled vehicles to protect the passengers in the car [1]. On

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the other hand, waste tire disposal becomes a significant issue to be considered in the world due to the vehicle industry's development. There are around 1.6 billion new tires generates per year and 1 billion waste tires each year worldwide. The waste tire is a great volume and a lot of void space that require valuable landfill space and need more than a hundred years to decompose. Hence, rubberized concrete that replaces sand aggregate with crumb rubber was produced, which can reutilizing scrap tires and enhance energy absorption under impact load at the same time.

A more recent study investigated rubberized concrete consisting of fine aggregate with crumb rubber has similar workability to normal concrete. The rubber enhances the flexural tensile strength, ductility, and damping ratio of concrete due to brittle concrete [2]. The impact resistance and energy dissipation of rubberized concrete also increased compared with normal concrete. However, it will reduce the concrete's density and compressive strength because the rubber is low bonding adhesion. Besides, the crumb rubber was more effective in increasing the strength of concrete than other forms of rubber, and the percentage of rubber replaced also affects the strength of concrete [3]

This research aims to develop the numerical procedure using the Finite Element Method (FEM) for effectively simulate modified rubberized concrete under impact loads. Rubberized concrete blocks with 10% of Rice Hush Ash (RHA) for cement substitution and crumb rubber replacement volume of sand with different percentages (0, 5, 10, 15, and 20%) were successfully modelled. The technology keeps moving, and numerical techniques became a popular method rather than experimental approaches. Finite Element Analysis (FEA) is the modelling of products and systems by setting up a virtual environment or condition to predict how the product reacts to the real-world forces, vibration, heat, fluid flow, and other physical effects. FEA is the application of the FEM to solve real engineering problems. This numerical simulation tool has good performance in time, energy, and cost-effectiveness.

The finite element model will connect these system points that are nodes to form the design's shape. However, the accuracy of the result is based on the model mesh, material descriptions, and structural properties [4]. Therefore, this study focuses on the material descriptions of Drucker-Prager (DP), Concrete Damage Plasticity (CDP), and Modified Drucker-Prager Cap (MDPC). The rubberized concrete mixes the characteristics of concrete and rubber particles. So, the material described by DP and MDPC for ductility of the crumb rubber, and CDP for the brittle cracking of concrete. The crumb rubber has a good performance to dissipate energy due to its elasticity characteristic compared with sand, gravel, and cement. Therefore, the rubberized concrete increases the energy absorption of concrete under impact load by reducing stress concentration and the brittleness of concrete, restraining or postponing the occurrence as well as the development of cracks [5]. Concrete with high energy absorption can apply in structure require high energy absorption such as road barrier to reduce the injuries and deaths during the accident.

2. Numerical Modelling

In this study, the numerical simulation of modified rubberized concrete under the impact loading was modelled using ABAQUS software. The practical work concerning the energy absorption of the modified rubberized concrete block under low-velocity impact loads was carried out by other researchers at the Universiti Tun Hussein Onn Malaysia. The size of the test specimen was 300 mm × 300 mm × 200 mm. A cylindrical projectile circular cross-section with a diameter of 40mm, a length of 800mm, and a weight of 80kg are used as an impactor of the test. The steel projectile was imposed on concrete specimens from a height of 1.6m.

2.1 Geometrical Design of Model

A three-dimension deformable model for rubberized concrete and steel projectile were constructed for analysis in ABAQUS. The 8-noded brick continuum elements (C3D8R) were created for the modified rubberized concrete. The element mesh with C3D8R and by symmetry revolved 360˚ to produce the cylindrical shape created for steel projectile to prescribe impact load.

2.2 Material Property of Model

The rubberized concrete element adopting three different material descriptions where are DP, MDPC and CDP. Table 1 shown the material properties of rubberized concrete with varying percentages of crumb rubber. In contrast, other parameter data and materials properties of steel projectile were taken from the previous study [6] shown in Table 2 and 3.

Table 1: Material properties of rubberized concrete.

RHA (%)	Crumb Rubber (%)	Mass Density, ρ_{rc} (kg/m^3)	Compression Strength, , f_{cu} (N/mm^2)	Tensile Strength, f_{st} (N/mm^2)	Young's Modulus, E (N/m^2)	Poisson's Ration, ν_c
0	0	2156	40.67	3.03	3.17E+6	0.20
10	5	2137	30.33	2.75	2.75E+6	0.17
10	10	2114	26.00	1.93	2.49E+6	0.16
10	15	2100	22.67	1.84	2.37E+6	0.15
10	20	2057	17.67	1.46	2.08 E+6	0.14

Table 2: Parameter of DP, MDP, and CDP taken from Mokhatar *et al.* [6]

CDP model parameters					
Dilation angle	Eccentricity, ε	σ_{bo}/σ_{co}	K_c	Viscosity parameter,μ	
38°	1	1.12	1	0.666	
DP model parameters					
Angle of friction, β		Flow stress ratio, K		Dilation angle, ψ	
30˚		1		20˚	
MDPC model parameters					
Material cohesion, *d* [N/m2]	Material angle of friction, β	Cap eccentricity parameter, *R*	Initial cap yield surface position	Flow stress ratio, *K*	Strain rate
4.71E+00	51°	0.65	0.0011	1	1.5

Table 3: Material properties of steel projectile taken from Mokhatar *et al.* [6]

Young's modulus, E_s [N/m2]	Poisson's ratio, ν_s	Density, ρ_s [kg/m3]	Yield stress, f_y [N/m2]	Ultimate stress, f_u [N/m2]
2.10E+11	0.29	7800	5.60E+08	6.30E+08

2.3 Initial and Boundary Conditions And Load

The initial velocity assigns to the penetration direction in order to simulate rubberized concrete's motion under impact loading. The boundary condition is assigned to the bottom node of the rubberized concrete block to avoid displacement or rotation, as Figure 1.

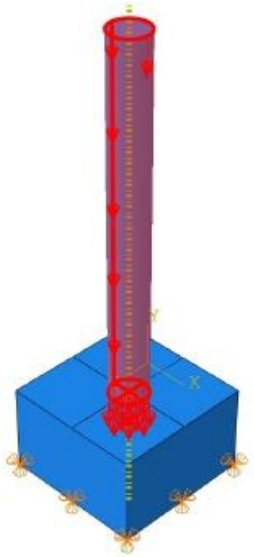


Figure 1: Loading and Boundary condition of modelling.

2.4 Projectile Simulation

All the steel projectile element nodes set an initial velocity of 4.0 m/s in a direction perpendicular to the surface rubberized concrete model. This value is given from experimental work carried out by other researchers in UTHM to compare the numerical and experimental result. In addition, the initial velocity of 5.0 m/s and 6.0m/s is also applied in this study as a projection to predict the energy absorption of modified rubberized concrete under different impact loads.

2.5 Energy absorption

The energy absorption was produced by the sudden collision between the rubberized concrete and projectile. The formula used to calculate the energy absorption shown in equation (1). The energy absorption of FEA calculation by using formula due to the FEA cannot directly provide the output of energy absorption. Therefore, the absorption FEA and experiment computed using the same formula can provide a better validation.

$$E_a = m.g.X \qquad Eq.\ 1$$

Where E_a is an energy absorption of rubberized concrete under the impact load, m is mass of the impactor, which is 80kg, g is the acceleration due to gravity at 9.81m/s^2 and X as the penetration depth of rubberized concrete after impact.

3. Results and Discussion

3.1 Mesh Density Sensitivity

The mesh sensitivity test aims to ensure the result of the FEA more sensibly accurate result. This mesh sensitivity test was only obtained for the concrete (0% RHA + 0% crumb rubber and simulate by using CDP model. The result of the FEA investigation utilizing various mesh densities for the rubberized concrete control sample is shown in Table 4 and Figure 2. It is indicated that the outcome of the FEM has been dramatically affected by the global size or the total number of elements. However, after the global size of 15, the penetration depth and calculated energy absorption do not change by an appreciable amount. Based on Kamal *et al.* [7], the processing time and storage required increased as the total element increased. Figure 2 shows that energy absorption of rubberized concrete increases as the total element increased and maintains consistently after the total element reach 5200. As per Kamal *et al*. [7], the purpose of the mesh sensitivity study was to ensure the accuracy of the result and save the computational cost required at the same time. Therefore, the total element increased after 5200 was not required due to without much increase of the accuracy of prediction energy absorption. The global size of 15 is selected for an appropriate meshing size of all specimen models.

Table 4: Result of mesh refinement with Energy Absorption within CDP region

Mesh density	Total elements	Penetration Depth of CDP model (mm)	E_a(J)
GB35	486	2.61	2.05
GB30	700	2.93	2.30
GB25	1152	2.83	2.22
GB20	2400	3.18	2.50
GB17	3888	3.35	2.63
GB15	5200	3.59	2.82
GB 13	8280	3.62	2.84

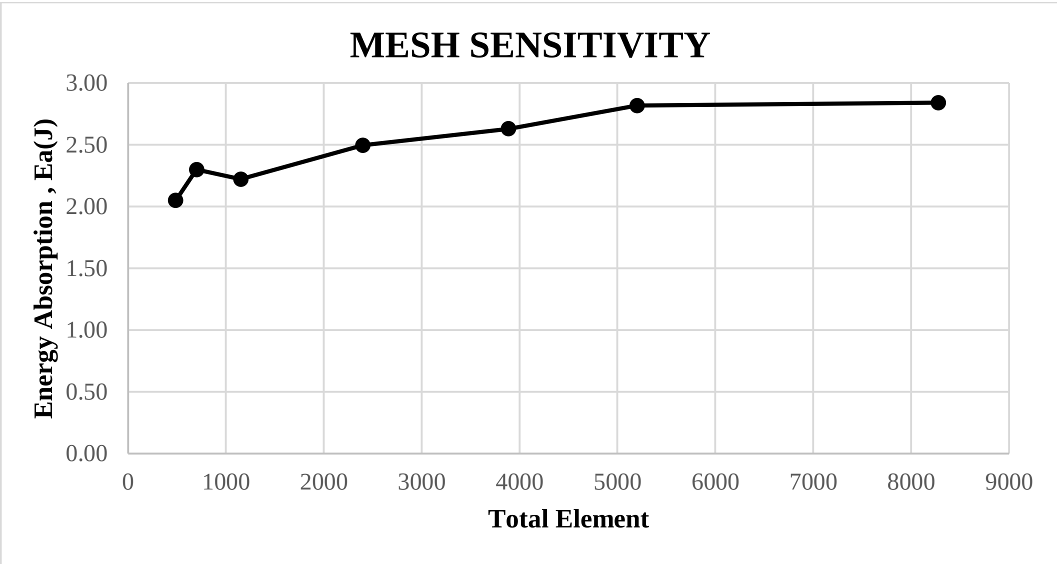


Figure 2: Result of mesh refinement for Energy Absorption within CDP region

3.2 Comparison of three material description

In this study, three different material description was used to simulate rubberized concrete. The energy absorption between the three model and experiment results, as well as its discrepancy are shown in Table 5. The average percentage discrepancies of all models are less than 20%, which is acceptable. The lowest average percentage discrepancy is CDP about 8.80%. The average percentage discrepancies of the DP and MDPC model were 13.71% and 19.94%, respectively. Figure 3 was presented the penetration depth of the three models compared to the experimental result. Although the DP model displays a good prediction of penetration depth, the penetration depth of CDP closer to an experimental result is more suitable for low-velocity impact [8]. Besides, MDPC obtained the highest percentage discrepancy for rubberized concrete block's energy absorption compared to the experimental result because the MDPC model has a better prediction interface between concrete and reinforced steel [9]. Figure 4 displays the energy absorption of three models compared to experimental. The energy absorption for the CDP model more nearly closed to the experimental result where has a better prediction. The difference in numerical accuracy of the three models is also contributed by the constitutive law of these models. The CDP modelling is based on the two main failure mechanisms as mentioned above, which means that the failure of the evolution of yield surface is controlled by two hardening variables. However, the DP model and MDPC model are constructed based on only one failure mechanism in tensile cracking and compressive crushing. The parameter of MDPC has an addition of a cap-shaped yield surface compared to the DP model. These reasons affect the overall performance of the three models and give the numerical accuracy differently. Further, concrete behaviour, including plastic behaviour, compressive behaviour, tensile behaviour, confinement, and damage mechanism, can well be replicated by using CDP model. As a result, there was no surprise that the CDP has a better correlation with experimental than other models [10]. Since the CDP model presents the best prediction result to the experiment result, therefore is an appropriate material model to predict the energy absorption of modified rubberized concrete under different impact loads.

Table 5: Energy Absorption of three model and experiment

		Energy Absorption, E_a(J)				Discrepancy %		
RHA (%)	Crumb Rubber (%)	Experiment	CDP	DP	MDPC	CDP	DP	MDPC
0	0	2.68	2.82	2.50	3.53	5.28	6.45	31.96
10	5	5.40	4.84	4.54	5.05	10.32	15.84	6.40
10	10	6.95	6.28	5.64	8.44	9.60	18.82	21.47
					Average	8.80	13.71	19.94

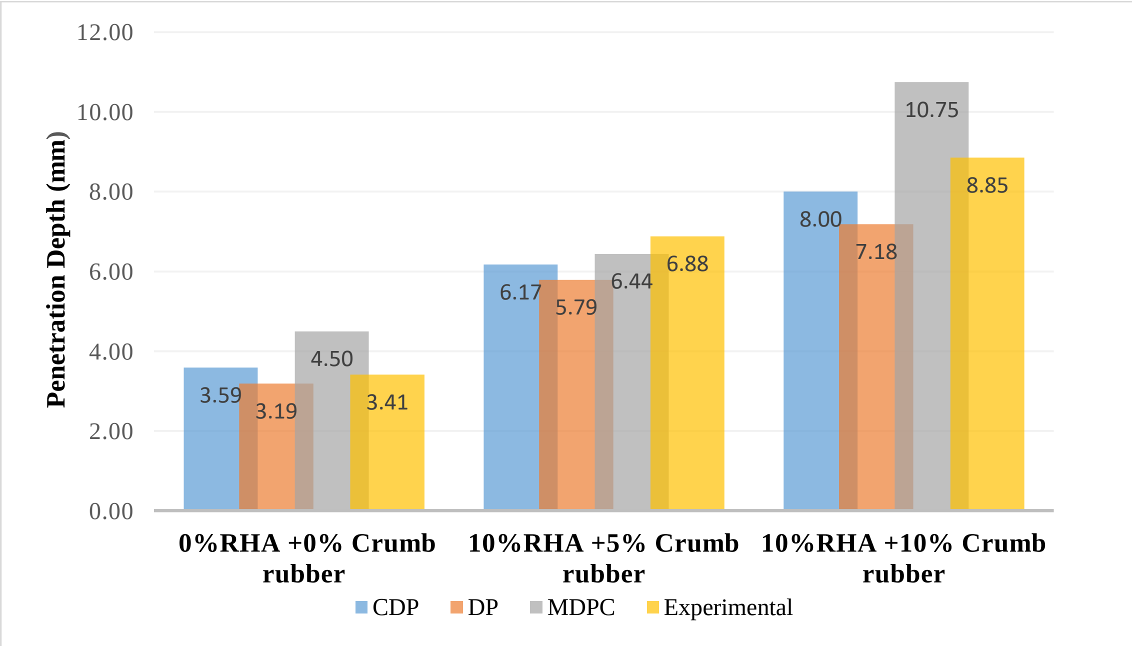


Figure 3: Penetration depth of rubberized concrete.

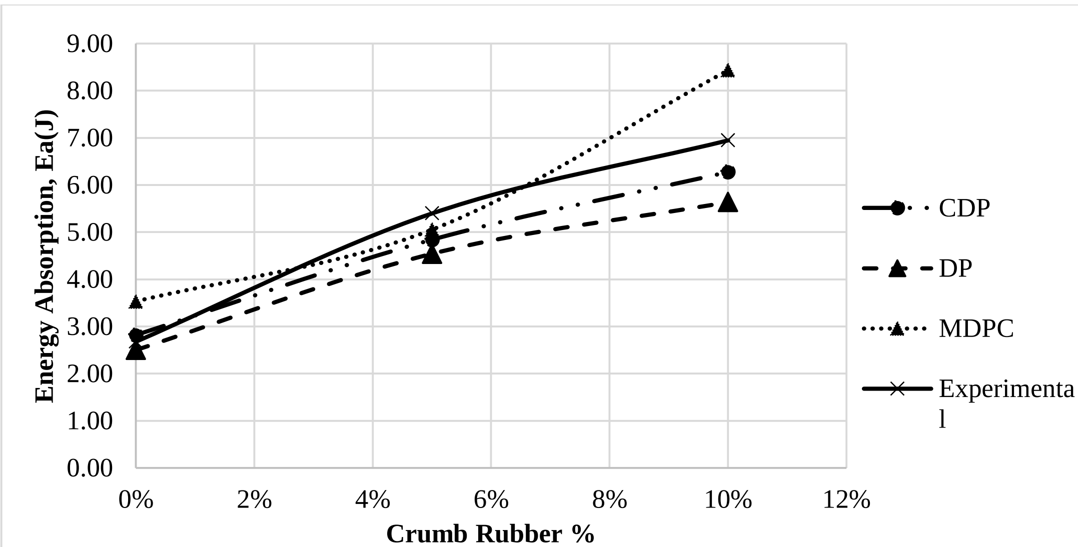
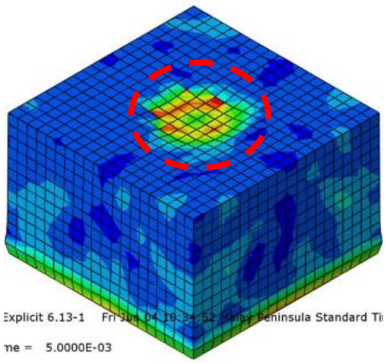


Figure 4: Energy absorption of rubberized concrete.

3.3 Failure of Rubberized Concrete

The failure mode of rubberized concrete from the FEM model and experimental are presented in Figure 5. In addition, the numerical model exhibits reasonably close to that demonstrated by the experimental work [11]. It can be observed that the general outline of damage after the impact of the numerical model and experimental are in close agreement. Therefore, the FEM models have a good prediction on the failure mode of the rubberized concrete. On the other hand, the crater that produced under constant impact velocity was wider when used rubber as the sand replacement and RHA as cement replacement. The growth of the crater width as the percentage of rubber increases.



(a)

(b)

Figure 5: Result for rubberized concrete with 10% crumb rubber and 10% RHA after impact test (a) FEM model and (b) Experimental

3.4 Rubberized concrete under different impact loads

From the previous section, the CDP model has better accuracy under impact. Therefore, the CDP model is used in the rubberized concrete block under various impact velocities to predict the penetration depth and energy absorption. The result was summarized in Table 6. From the table, the penetration depth of rubberized concrete was increased as the percentage of crumb rubber are also increase. This is due to the fracture of rubberized concrete under impact is softer than concrete without rubber. The rubber particles as the sand replacement can eliminate the stress concentration of void and delay cracks' occurrence and development [12]. Rubberized concrete can burden more deformation compared to normal concrete. As a result, the deformation of rubberized concrete increases as the percentage of crumb rubber increases.

On the other hand, the higher the percentage of crumb rubber, the higher the energy absorption of rubberized concrete, as shown in Table 6. The rubberized concrete with 10% RHA and 20% rubber presented the highest energy absorption. The flexibility of concrete increased by the addition of rubber and allow rubberized concrete to resist more impact, which means absorb more energy [13]. As mentions above, the rubber can fill the void of the concrete with the help of cementation to increase the density of rubberized concrete. The deceleration of impact increase as the plastic density increase [14]. Therefore, rubberized concrete can absorb or burden more energy compared to normal concrete, and the rubberized concrete with 20% rubber presented as optimum impact resistance and energy absorption [15].

However, the addition of rubber causes the compressive strength and brittleness of concrete to decrease. It can directly give an affect on the ability of energy absorption [16]. The addition of RHA plays a vital role to minimize the reduction of compressive strength and brittleness of rubberized concrete. The penetration depth of rubberized concrete increases as the rubber percentage increase, which the rubberized concrete does not lose too much strength under the help of RHA and has a good performance in energy absorption. Figure 6 was presented the energy absorption of rubberized concrete under different impact velocities. The energy absorption of rubberized concrete also increases as the percentage of crumb rubber increase under various velocities. The higher the impact velocity, the higher of energy absorption. The higher of velocity collide between rubberized concrete and projectiles steel, the higher kinetic energy produced. Therefore, more energy transfer to rubberized concrete for energy absorption.

Table 6: FEM result of rubberized concrete under different impact loads.

Velocity (m/s)	RHA (%)	Rubber (%)	Penetration Depth (mm)	E_a(J)
4	0	0	3.59	2.82
	10	5	6.17	4.84
	10	10	8.00	6.28
	10	15	8.05	6.32
	10	20	9.07	7.12
5	0	0	5.56	4.36
	10	5	9.52	7.47
	10	10	12.31	9.66
	10	15	12.33	9.68
	10	20	13.85	10.87
6	0	0	8.43	6.62
	10	5	13.65	10.71
	10	10	17.02	13.36
	10	15	17.03	13.37
	10	20	18.61	14.61

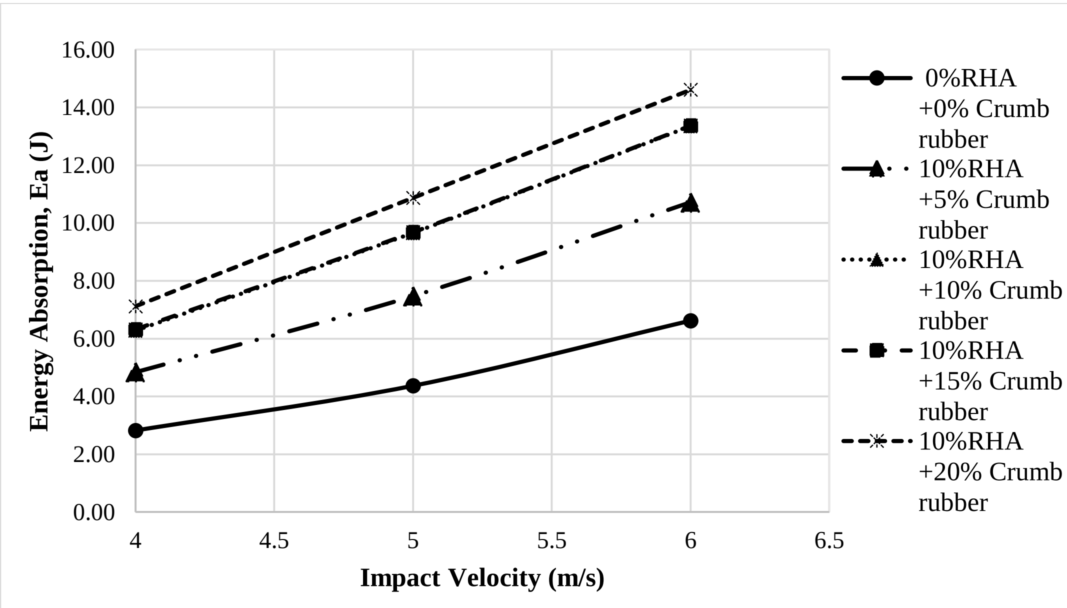


Figure 6: Energy absorption of rubberized concrete under different impact velocities.

4. Conclusion

An impact load test of rubberized concrete was successfully simulated by adopting three material descriptions, including DP, CDP, and MDPC. The numerical procedure using the FEM to effectively simulate modified rubberized concrete under impact loads were investigated accordingly. The CDP model produced a high accuracy result of FEM modelling compared with DP and MP. The average discrepancy percentage of the CDP model was 8.80% which is lower than DP and MDPC with 13.71% and 19.94%, respectively. The failure profile of rubberized concrete in the model is almost similar to the experiment's observation. Further, the growth of the crater widths is affected by the increment percentage of rubber. The CDP model has presented a better correlation with experimental compared to DP and MDPC models. Therefore, the CDP model was more suitable to replicate the rubberized concrete modelling under low-impact force. It can be concluded that crumb rubber in concrete generates a good result for energy absorption. The elastic behaviour of concrete increased by the addition of rubber to resist more impact, which means absorb more energy. Besides, 10% of RHA for cement substitution was helpful for rubberized concrete to minimize the reduction of compressive strength and brittleness mechanism. More investigation of rubberized concrete under dynamic load is recommended to explore the dynamic response of rubberized concrete as a road barrier to reduce the injuries and deaths during road accident.

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