agriculture

Article

Compression Strength and Critical Impact Speed of Typical Fertilizer Grains

Mingjin Xin, Zhiwen Jiang, Yuqiu Song *, Hongguang Cui, Aiju Kong, Bowen Chi and Renbao Shan

College of Engineering, Shenyang Agricultural University, Shenyang 110866, China; xinmj@syau.edu.cn (M.X.); 2021220005@stu.syau.edu.cn (Z.J.); chg7763@syau.edu.cn (H.C.); 2005500004@syau.edu.cn (A.K.); chibw@neusoftmedical.com (B.C.); shanrenbao@tdgcore.com (R.S.)

* Correspondence: songyuqiu@syau.edu.cn

Abstract: The application of fertilizer is necessary for the growth and yield of crops, especially for paddy rice. Precision application is important for the fertilizer utilization rate and sustainable development of agriculture. However, the crushing of fertilizer grains will reduce the quality of fertilization, for the decrease in the size and mass of the fertilizer particles and the degree of crushing mainly depend on the physical and mechanical properties of the fertilizer grains. In this study, the compression strength and critical impact speed of four typical commonly used fertilizer grains, a compound fertilizer of nitrogen, phosphorus, and potassium (NPK compound fertilizer), organic fertilizer, large granular urea, and small granular urea, were measured and analyzed. The static compression test was carried out using a TMS-Pro texture analyzer and the results show that the four kinds of fertilizer grains are brittle materials, and their elastic moduli are 208 MPa, 233 MPa, 140 MPa, and 107 MPa, respectively; the theoretical impact model of fertilizer granules is established based on the compression test result and Hertz elastic contact theory, the theoretical formula for the critical impact speed of fertilizer grains is derived, and the theoretical critical impact strength and speed are worked out. An image capture system for the impact process of fertilizer grains was developed, and the impact test was conducted. The results show that the critical impact speed of the four kinds of fertilizer grains decreases with the increase in granule size, while the variance analysis shows that the effect is not significant. The comparison of the experimental results with the theoretical values shows that the theoretical formula could be used to predict the trends of the critical impact speed of fertilizer grains. The model was optimized with the MATLAB 2018 function fitting tool based on the test and analysis. The goodness of fit of the formula is 0.824, which is 13.43% greater than that of the original theoretical formula, indicating that the modified formula based on the compression test data might estimate the critical impact speed of the granular fertilizer with brittle material properties more accurately. The results may provide a reference for the parameter design of a precision fertilization machine.

Keywords: fertilizer granules; elastic modulus; compressive strength; critical impact speed; fitting model; breakage characteristics

Citation: Xin, M.; Jiang, Z.; Song, Y.; Cui, H.; Kong, A.; Chi, B.; Shan, R. Compression Strength and Critical Impact Speed of Typical Fertilizer Grains. *Agriculture* **2023**, *13*, 2285. https://doi.org/10.3390/agriculture13122285

Academic Editor: Jin He

Received: 17 November 2023
Revised: 12 December 2023
Accepted: 14 December 2023
Published: 16 December 2023

1. Introduction

Applying fertilizers is one of the effective measures to increase crop yield [1,2]. Most of the traditional fertilization for the paddy field is carried out manually, especially during the growth of paddy rice: it is of low efficiency and poor operation quality, and has a high labor intensity and cost [3]. Mechanized precision fertilizer application can significantly improve the utilization rate of the fertilizer and promote the sustainable development of agriculture [4,5].

The physical and mechanical properties of the fertilizer will affect its moving characteristics in the fertilization machine, which, in turn, affects the selection of the component materials and the design of the structural parameters [6]. The parameters of granular fertilizers, such the size, density, coefficient of friction, suspension speed, coefficients of restitution, collision recovery coefficient, and elastic modulus, were studied [7–9], and the interaction properties of fertilizer particles were investigated as well [10]. Xiao Wenli analyzed the influence of the fertilizer shape and particle size distribution on the flow parameters [6]. Song et al. calibrated the contact parameters of fertilizer particles in an EDEM simulation, including the restitution coefficient, static friction coefficient, rolling friction coefficient, etc. [11]. These studies provide a basis for the design of the fertilization machine.

While, during the fertilization operation, the collision of fertilizer granules with the working parts of the application device is unavoidable, especially in pneumatic and disc centrifugal fertilizer spreaders, the fertilizer granules may hit against the wall of the application device at a high speed.

When the collision speed is great enough, the fertilizer granules may break, the size will reduce, and the distribution range of the particle size of the fertilizer will increase, which result in the decrease in the kinetic energy of the granules and the increase in energy differences among fertilizer particles, and the motion trajectories vary accordingly, which will lead to the decrease in the uniformity and precision of the fertilizer distribution in the field [12–14]. The degree of crushing of fertilizer grains mainly depends on the physical and mechanical properties of the fertilizer grains [3]. Wang Lei carried out an elastic collision analysis on the contact process between the fertilizer particles and distribution device, obtained the factors affecting the crushing of the fertilizer particles, and determined the optimal structural type for the distribution device [15]. However, the relationship between the critical impact speed which may break the fertilizer particles with the mechanical properties of the fertilizer particle is still not clear.

Therefore, the mechanical behaviors of four typical fertilizers commonly used in agricultural production under static compression and dynamic impact were studied, to provide references for developing the technology and equipment of fertilizer application.

2. Materials and Methods

2.1. Experiment Material

The fertilizer samples selected for the study are compound fertilizer of nitrogen, phosphorus, and potassium (NPK compound fertilizer) produced by Hebei Jiheng Group Co., Ltd. (Hengshui, China) (main components of nitrate nitrogen, P_2O_5, K_2O, the total nutrients $\geq$ 45%, water content of 1.88%), organic fertilizer produced by Liaoning Jiaji Crop Nutrition Co., Ltd. (Shenyang, China). (organic matter content $\geq$ 40%, N-P_2O_5-K_2O content $\geq$ 5%, water content of 2.49%), large granular urea produced by China National Coal Group Corp. (Beijing, China) (water content of 0.83%), and small granular urea produced by CNOOC Tianye Chemical Co., Ltd. (Huhehaote, China) (water content of 0.66%) (as shown in Figure 1).

Figure 1. Four kinds of fertilizer granules for testing.

The size distribution of fertilizer granules was obtained based on triaxial dimensions measurement and geometric mean diameter calculation of fertilizer grains (as shown in Figure 2) [16]. Three typical sizes from the size range of intensive fertilizer granules are selected for the impact test, and the size error of the selected fertilizer particles was controlled within ±0.1 mm (as shown in Table 1).

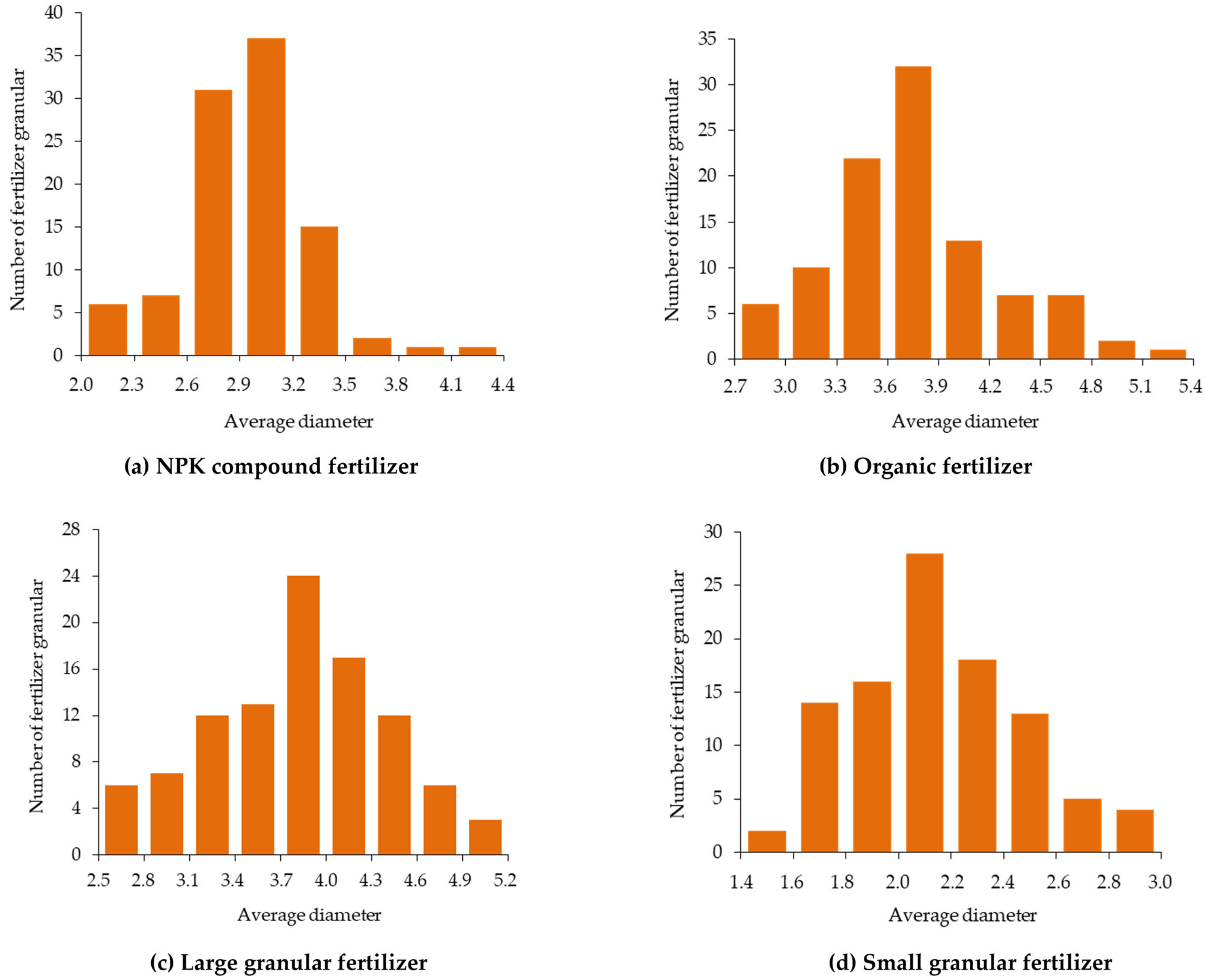


Figure 2. Particle size distribution of four kinds of fertilizer particles.

Table 1. Granule diameter of various fertilizers used in impact experiment.

Fertilizer Variety	Fertilizer Granule Size (mm)		
NPK compound fertilizer	2.5 ± 0.1	3 ± 0.1	3.5 ± 0.1
Organic fertilizer	3.2 ± 0.1	3.8 ± 0.1	4.4 ± 0.1
Large granular urea	2.5 ± 0.1	3.5 ± 0.1	4.5 ± 0.1
Small granular urea	1.5 ± 0.1	2 ± 0.1	2.5 ± 0.1

The materials of target board used in the impact test are PVC, ABS, PMMA, and 304 stainless steel. The inelastic parameter λ of collision between ball and board can be calculated using Formula (1) [17]:

$$\lambda = \frac{\pi^{\frac{3}{5}}}{\sqrt{3}}\left(\frac{r}{H}\right)^2\left(\frac{v}{v'}\right)^{\frac{1}{5}}\left(\frac{\rho_1}{\rho_2}\right)^{\frac{3}{5}}\left(\frac{\frac{E_1}{1-{\mu_1}^2}}{\frac{E_1}{1-{\mu_1}^2}+\frac{E_2}{1-{\mu_2}^2}}\right) \quad (1)$$

where r is mean sphere radius, m; H is board thickness, m; v is impact velocity, m/s; v' is normal wave velocity in the target board, m/s; ρ_1 and ρ_2 are densities of the ball and board, kg/m^3; E_1 and E_2 are modulus of the ball and boards, Pa; and μ_1 and μ_2 are Poisson's ratio of the ball and boards.

Among them, the elastic modulus, density, and Poisson's ratio of the target board were determined according to the handbook and experiments [4,18]. The remaining unknown parameters were selected based on related literature [17]. The basic mechanical parameters and the final dimensions of the target board are shown in Table 2.

Table 2. Physical and mechanical parameters of target boards.

Target Board Material	Elastic Modulus (GPa)	Poisson's Ratio	Length (mm)	Width (mm)	Thickness (mm)
PVC	0.55	0.4	100	40	6
ABS	0.52	0.4	100	40	6
PMMA	1.4	0.4	100	40	5
304 stainless steel	195	0.3	100	40	3

2.2. Instruments and Equipment

In this study, DL91150 digital Vernier caliper (Deli Group Co., Ltd., Ningbo, China). (accuracy of 0.01 mm) was used to measure the three-axis size of fertilizer granules; the Shuangjie JJ523BC electronic precision balance (Beijing Jinkelida Electronic Technology Co., Ltd., Beijing, China) (maximum range of 500 g, accuracy of 0.001 g) and measuring cylinder were used to measure the density of fertilizer; and a TMS-Pro texture analyzer (FTC Co., Ltd., London, OH, USA) was used in the static compression test of fertilizer particles. An image capture system for recording fertilizer granule impact process (Figure 3) was designed for the impact test. The image is captured using a high-speed camera PLEXLOGGER (Shinano Kenshi Co., Ltd., Nagano-ken, Japan) (maximum shooting speed of 100,000 FPS; maximum resolution of SXGA (1280 × 1024)), which mainly consists of camera, built-in light source, and analyzer.

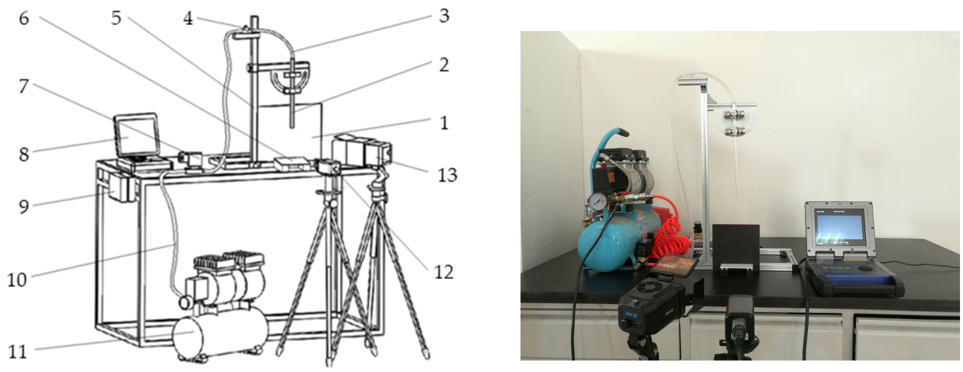


Figure 3. Image capture and testing system for fertilizer particle state during impact process: 1. back-board; 2. jetting tube; 3. guide tube; 4. feeding tube 5. support 6. target board; 7. solenoid; 8. analyzer host; 9. controller; 10. air pipe; 11. air compressor; 12. high speed camera; 13. light source.

2.3. Test Plan

2.3.1. Static Compression Test of Fertilizer Granules

The compressive property parameters of fertilizer granules are obtained through uniaxial compression test, to provide a basis for the establishment of theoretical impact model of fertilizer granules.

In order to facilitate the observation of the changes of fertilizer granules during compression and ensure the accuracy of test data, fertilizer granules with larger size and higher sphericity (>97%) were selected as compression samples in this study. The granule size fluctuation was controlled within the range of ±0.1 mm (as shown in Table 3). The sphericity φ was calculated using Formula (2) [16]:

$$\varphi = \frac{(LWT)^{1/3}}{L} \tag{2}$$

where L is mean fertilizer length, mm; W is mean fertilizer width, mm; and T is mean fertilizer thickness, mm.

Table 3. Equivalent granule diameter of fertilizer used in compression test.

Fertilizer Variety	Equivalent Granule Diameter (mm)
NPK compound fertilizer	3 ± 0.1
Organic fertilizer	3.5 ± 0.1
Large granular urea	3.5 ± 0.1
Small granular urea	2 ± 0.1

Figure 4 shows the texture analyzer used in the compression test. In the test, fertilizer sample is placed under the center of the indenter, and as close as possible to the indenter, then we set the pressure and position parameters of the indenter to zero, and start the preset compression program to obtain a downward movement of the indenter at a speed of 2 mm/min. When the compression displacement reaches 1 mm, the compression is set to stop and the indenter will return to the starting position at a speed of 40 mm/min. The compression force and displacement of fertilizer granules during the test are recorded by analysis software. Twenty fertilizer granules of each size class are tested for static analysis.

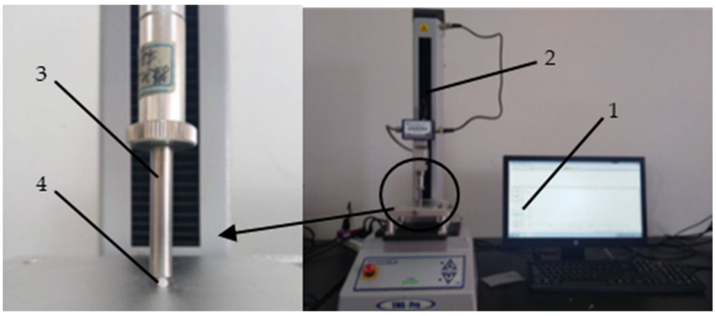


Figure 4. Fertilizer particle compression test: 1. computer; 2. texture analyzer; 3. indenter; 4. fertilizer particle.

2.3.2. Fertilizer Granule Impact Test

During the fertilizer application process, the greater the impact speed of fertilizer granule on the wall of the device, the higher the possibility for its breakage. According to the Hertz elastic collision theory, when the size and material properties of fertilizer granules and the target board are certain, the impact is mainly related to the relative speed of the fertilizer granule impacting on the target board [19]. Therefore, the impact test was carried out to determine the critical impact speed of fertilizer granules in this study.

(1) Definition of critical fracture state

It was observed from the trial test that the state of different types of fertilizer granules with different sizes were similar after impacting on the target board. The four typical states of large granules of urea captured by high-speed camera at a shooting frequency of 16,000 FPS after impacting on a 304 stainless steel board are shown in Figure 5. With gradual increase in the collision speed, four typical conditions, complete (the particles bounce), damaged, broken, and shattered, of the fertilizer granules will appear. When bounce occurs, the main body of granule is complete; when damage occurs, there will be small fragments off granule after impact, but the change is not obvious, and the main body of the granule still exists; when the impact speed increases, the fertilizer grains break into some large pieces (broken state); when the speed increases further, the fertilizer granules may shatter into small pieces, and the main body of the granule no longer exists.

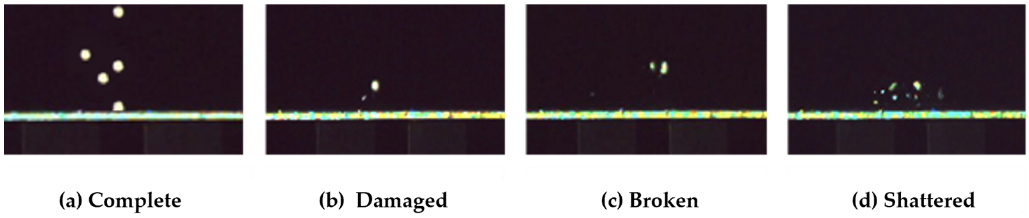


Figure 5. Typical states of large granular urea impacted on 304 stainless steel board.

The "damaged" condition after impact is taken as the critical state of the fertilizer grain in this study, according to related research on critical impact damage of granular objects, and the speed, which results in the damage, is taken as the critical impact speed of fertilizer granule [20,21].

(2) Experiment method

A pneumatic acceleration device was designed to accelerate fertilizer granules to the critical impact speed with compressed airflow. The pressure range of air compressor was determined through trial tests.

(i). Trial test of pressure range

In the test, the critical impact speeds of four kinds of fertilizer granules with three size grades were measured. The pressure of the air compressor is adjustable between 0 and 0.7 MPa. The impact states of 20 fertilizer granules were captured at every 0.05 MPa to determine the maximum air pressure P_1 at which all fertilizer grains bounce after impacting on the target board, and the minimum air pressure P_2 at which all fertilizer grains break into small pieces. Then, P_1–P_2 was set as the range of air pressure for the impact test. The high-speed camera shooting frequency was set to 16,000 FPS and the recording time was 0.48 s to capture clearly the state after fertilizer granules impacted on target boards.

(ii). Determination of critical impact speed

The air pressure was set at P_2 at beginning of the test, then we put a fertilizer granule in the jetting tube, and turn on recording button on the analyzer host and the airflow valve switch, to obtain the video of impact process. With each injection, the pressure in the cylinder decreases, and we repeat the test process until the pressure in the cylinder drops to P_1, then turn on the air compressor, and recharge the cylinder pressure to P_2, then repeat the above operation until 50 videos of fertilizer grains in critical breaking process are captured.

3. Results and Discussion

3.1. Compressive Properties of Fertilizer Granules

Figure 6 shows the typical compressive force-deformation curve of the four typical fertilizer granules. It can be observed that the four kinds of fertilizer granules have great differences in compressive strength, but the compressive failure characteristics are similar. In the early stage of loading, the relationship between the compression force and deformation of the fertilizer grain is basically linear, indicating that the fertilizer granules are elastic in this stage. When the compressive force on the fertilizer granules reaches a peak value, cracks will appear on the fertilizer granules and they would rapidly develop and connect together, which would cause the splitting of the fertilizer granules, resulting in a rapid reduction in compression force. There are no obvious yield points from the elastic deformation to the failure of the fertilizer grains.

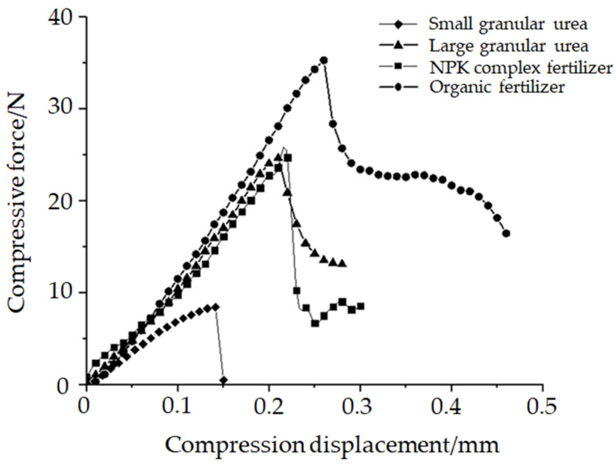


Figure 6. Compressive force-deformation curve of fertilizer granules.

It can be concluded from the compression test curve and phenomenon that the breaking feature of the fertilizer granules under compression is conformed to that of brittle materials; that is, the fertilizer used in this study could be regarded as elastomers before material failure occurred, and it breaks up eventually under a certain peak stress, due to the increase in and the connection of the internal fracture accumulation of the fertilizer grains [22–24]. The modulus of elasticity is one of the important parameters affecting the breakage of brittle materials [19]; the apparent elastic modulus of fertilizer granules is calculated theoretically with Formula (3) [25] based on the maximum damage force and deformation data of fertilizer granules obtained through compression tests.

$$E = \frac{3F_0\left(1-\mu^2\right)}{4D^{\frac{3}{2}}R^{\frac{1}{2}}} \quad (3)$$

where E is the elastic modulus, Pa; F_0 is the compression load, N; μ is Poisson's ratio; D is the compression deformation, m; and R is the curvature radius of the test sample at the contact point, m.

Table 4 shows the compressive mechanical parameters of the fertilizer granules obtained through statistical calculation.

Table 4. Mechanical properties of fertilizer particle under compression.

Fertilizer Variety	Mean Value of Maximum Compression Force (N)	Mean Value of Maximum Deformation (mm)	Apparent Elastic Modulus (MPa)
NPK compound fertilizer	30.74 ± 1.35	0.187 ± 0.020	208
Organic fertilizer	42.52 ± 1.86	0.246 ± 0.025	233
Large granular urea	25.58 ± 0.96	0.222 ± 0.023	140
Small granular urea	8.00 ± 0.24	0.143 ± 0.018	107

3.2. Theoretical Calculation of Critical Impact Speed

When the speed of fertilizer granules hitting the target board is not higher than the critical impact speed, the main body of the granules remained intact without damage, the granules are in the stage of elastic deformation according to the compression characteristics, the properties of the granules can be studied based on the Hertzman elastic contact theory [26], and the impact stress of the contact center of the granules upon hitting the target board can be calculated with Formula (4) [27]:

$$P = \frac{3}{2\pi}\left(\frac{4E^*}{3R_e}\right)^{\frac{2}{3}}F^{\frac{1}{3}} \quad (4)$$

where P is the impact stress of the contact center, Pa; E^* is the equivalent elastic modulus, Pa; R_e is the equivalent contact radius, m; and F is the impact force, N.

The impact force F is related to the elastic deformation of granules upon hitting target board. The relationship between them can be demonstrated through Formula (5):

$$F = \frac{4E^*}{3}\sqrt{\frac{R_e\delta^3}{F_2(e)^3}} \tag{5}$$

where δ is the impact deformation, m; and F_2 (e) is the ovality correction factor.

The F_2 (e) is taken as 1 in this study due to the high sphericity of the fertilizer granules. It could be known from the two formulae above that the impact force and impact stress reach their peak values when the granule deformation reaches the maximum value, and the granule would be most likely to break. At this moment, the kinetic energy of the granule would be fully converted into the deformation energy of the target board and the granule itself, that is:

$$\int_0^\delta F\mathrm{d}\delta = \frac{1}{2}m_e v^2 \tag{6}$$

where v the is impact speed, m/s; and m_e is the equivalent mass of the collision object, kg.

Therefore, it could be deduced that:

$$\delta_{max} = \left(\frac{15m_e v^2}{16E^*\sqrt{R_e}}\right)^{\frac{2}{5}} \tag{7}$$

where δ_{max} is the maximum deformation during the impact process, m. It could be obtained from the above four formulae that:

$$P_{max} = \frac{3}{2\pi}\left(\frac{4E^*}{3R_e^{\frac{3}{4}}}\right)^{\frac{2}{3}}\left(\frac{5m_e v^2}{4}\right)^{\frac{1}{15}} \tag{8}$$

where P_{max} is the maximum contact center stress of the granule in the impact process, Pa.

The formulae for the equivalent mass and equivalent contact radius in Formula (8) are as follows:

$$\frac{1}{m_e} = \frac{1}{m_f} + \frac{1}{m_t}, \frac{1}{R_e} = \frac{1}{R_f} + \frac{1}{R_t} \tag{9}$$

where m_f is the granule mass, kg; m_t is the target board mass, kg; R_f is the granule curvature radius, m; and R_t is the target board curvature radius, m.

Since the mass of the target boards are much larger than that of the fertilizer granules, this study takes $R_e \approx R_f$, $m_e \approx m_f$ in the calculation. Then, the calculation formula for the critical impact speed of the fertilizer granules upon hitting the target board is:

$$v_l = 1.56\sqrt{\left(\frac{\sigma_l^5}{\rho E_I^4}\right)} \tag{10}$$

where v_l is the critical impact speed of the fertilizer granules, m/s; E_I is the comprehensive elastic modulus of the fertilizer granule and target board, Pa; σ_l is the critical impact stress, Pa; and ρ is the fertilizer density, kg/m^3, which is measured by the drainage method in this study [16].

The comprehensive elastic modulus is calculated as:

$$\frac{1}{E_I} = \frac{1-\mu_f^2}{E_f} + \frac{1-\mu_t^2}{E_t} \tag{11}$$

where E_f is the elastic modulus of the fertilizer granule, Pa; E_t is the elastic modulus of the target board, Pa; μ_f is the Poisson's ratio of the fertilizer granule, which is taken as 0.25 [16]; and μ_t is Poisson's ratio of the target board.

It can be concluded from Formula (10) that the critical impact speed of the fertilizer granules is only related to the inherent properties of the materials, such as density, critical impact stress, and elastic modulus, but less related to the size of the fertilizer granules. In addition, the breakage of the fertilizer grains followed the normal stress fracture criterion, due to the brittle property. That is, the critical impact stress of the fertilizer is equal to the ultimate compression stress. Table 5 shows the critical impact stress and speed of the fertilizer granules which are worked out with Formulas (4) and (10), using the compression mechanical characteristic parameters of the fertilizer granules in Table 4.

Table 5. Calculated value of critical impact strength parameters of fertilizer granules.

Fertilizer Variety	Critical Impact Stress (MPa)	Critical Impact Speed on Different Target Boards (m/s)			
		ABS	PVC	PMMA	304
NPK compound fertilizer	55.96	30.116	29.156	20.242	15.365
Organic fertilizer	54.10	35.99	34.934	25.048	19.555
Large granular urea	36.66	23.953	23.432	18.447	15.554
Small granular urea	27.27	17.832	17.521	14.504	12.713

3.3. Results and Discussion of Impact Test

3.3.1. Effect of Granule Size on Critical Impact Speed

The results of the four types of fertilizers with three particle sizes hitting on the target boards are given in Tables 6–9. The relationship between the critical impact speed and the size of the fertilizer particles are shown in Figure 7. The p value obtained from the variance analysis of the influence of the fertilizer granule size on the critical impact speed is shown in Table 10.

Table 6. Critical impact speed of NPK compound fertilizer impacting on target boards.

Target Material	ABS			PVC			PMMA			304		
Particle size/mm	2.5	3	3.5	2.5	3	3.5	2.5	3	3.5	2.5	3	3.5
Critical impact speed/m·s^{-1}	27.79	26.74	26.92	26.94	27.33	25.42	20.73	22.17	21.40	18.64	19.04	18.68
	26.48	27.27	28.42	26.60	26.68	26.17	22.65	22.20	20.81	18.93	18.79	18.05
	26.39	26.52	26.98	27.53	27.40	27.10	20.67	20.23	21.00	19.60	19.12	19.05
	28.59	28.44	27.02	26.93	27.53	25.56	20.97	21.77	21.58	18.34	19.91	17.66
	28.40	27.95	27.98	26.76	28.26	25.84	20.38	21.20	21.07	18.28	19.31	18.62
	27.83	26.94	28.09	27.37	26.50	26.42	22.18	20.64	20.32	18.75	18.51	17.55
	28.29	28.17	26.42	27.00	27.97	27.24	21.80	21.23	20.87	20.31	18.60	19.16
	28.54	28.49	26.72	26.70	26.50	27.23	21.10	20.29	21.17	19.91	18.37	18.43
	28.26	28.15	28.47	27.57	26.07	25.98	20.56	20.87	21.19	20.34	19.15	18.83
	27.92	28.00	28.02	26.98	25.94	27.01	21.13	22.07	20.27	19.77	17.85	19.21
	28.45	26.91	26.96	26.58	27.03	27.66	22.11	20.52	20.67	18.08	17.90	18.13
	28.48	27.45	27.02	28.17	25.59	26.04	20.94	21.73	20.53	20.24	19.66	19.33
	28.61	26.70	27.20	28.15	26.41	25.96	22.38	20.76	20.73	19.36	18.29	18.68
	27.91	27.82	26.67	27.35	27.17	25.84	21.13	22.19	21.56	19.84	19.12	18.95
	27.36	28.35	28.49	27.27	27.12	26.13	21.36	21.43	21.31	19.95	19.76	18.95
	26.70	27.94	26.52	26.27	25.70	27.70	21.96	22.08	21.01	18.93	19.60	19.42
	28.38	27.64	26.56	26.75	26.79	25.99	21.55	20.07	21.40	18.83	19.60	17.95
	28.84	27.34	26.51	27.14	27.19	27.20	21.83	22.11	20.67	20.32	18.55	19.87
	26.79	28.74	28.31	27.21	25.77	26.15	21.89	21.41	21.22	19.05	18.18	19.91
	27.71	26.73	27.93	26.84	26.94	27.33	20.63	21.15	20.89	18.31	20.02	18.92

Table 7. Critical impact speed of organic fertilizer impacting on target boards.

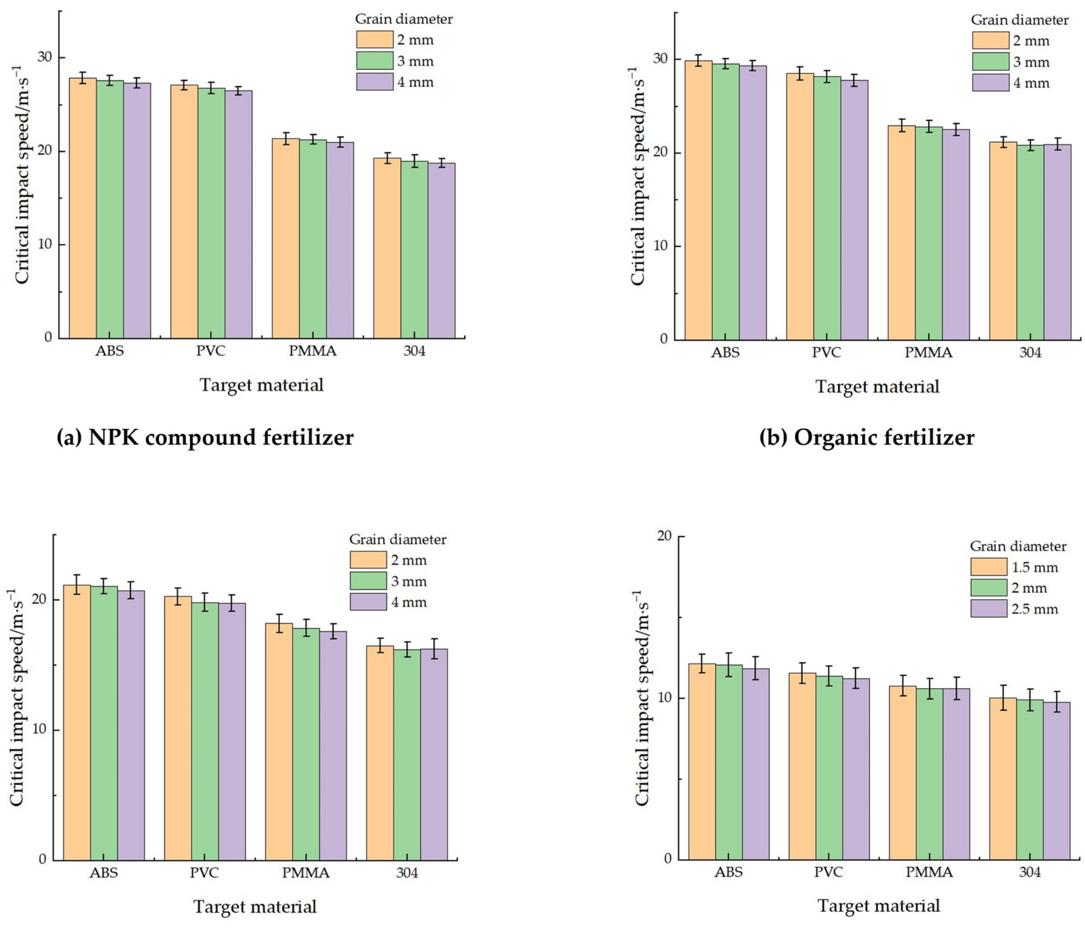
Target Material	**ABS**			**PVC**			**PMMA**			**304**		
Particle size/mm	3.2	3.8	4.4	3.2	3.8	4.4	3.2	3.8	4.4	3.2	3.8	4.4
Critical impact speed/m·s^{-1}	30.11	28.73	28.54	29.50	28.04	28.04	23.70	23.53	22.38	20.95	21.24	21.29
	29.32	29.80	29.17	29.70	28.82	27.97	21.86	22.35	22.07	20.90	21.44	21.95
	30.73	28.62	29.84	27.08	28.87	27.28	23.36	22.40	22.73	20.93	20.64	20.48
	29.63	29.25	30.13	28.78	27.35	28.23	23.96	21.75	23.77	21.96	20.84	20.00
	29.45	30.09	29.81	29.00	29.09	26.65	22.74	23.17	22.75	20.29	21.12	21.58
	29.17	28.92	29.20	29.58	28.39	26.51	22.99	22.88	22.16	20.54	20.67	21.04
	30.65	29.53	30.38	27.88	27.02	28.15	22.98	23.55	22.02	21.87	20.49	21.67
	29.62	30.34	30.39	27.54	27.65	29.22	23.19	22.16	22.66	21.93	20.15	20.79
	30.70	28.56	28.56	27.97	27.10	29.15	21.97	21.98	21.69	21.13	20.84	21.26
	29.27	30.67	29.12	29.27	27.62	28.88	23.09	23.01	22.85	21.82	20.99	20.45
	29.32	30.76	27.91	28.29	28.67	28.33	22.61	23.38	22.45	20.08	19.91	20.67
	29.85	29.89	29.28	27.48	28.14	28.76	23.79	23.33	21.62	21.86	20.22	21.65
	29.29	30.38	29.74	29.11	28.99	27.98	22.73	22.65	22.21	21.38	21.63	20.16
	30.48	28.45	29.76	28.65	28.64	27.27	23.98	23.47	23.78	20.51	21.74	19.86
	30.88	29.46	29.30	26.96	28.72	27.10	21.85	22.76	22.93	21.61	20.56	21.28
	29.02	28.75	28.72	29.14	28.52	27.17	23.73	22.14	21.54	20.03	20.12	20.60
	30.86	29.23	29.86	28.51	28.39	29.17	22.39	23.64	23.33	21.50	21.61	21.21
	29.17	30.54	28.42	29.06	28.85	28.93	23.79	23.14	23.10	20.82	20.47	21.32
	30.64	29.04	29.24	28.80	27.64	27.78	22.12	23.56	23.01	21.70	20.60	21.23
	29.58	30.27	29.61	28.26	27.24	26.85	22.34	22.04	21.46	21.87	21.42	20.78

Table 8. Critical impact speed of large granular urea impacting on target boards.

Target Material	**ABS**			**PVC**			**PMMA**			**304**		
Particle size/mm	2.5	3.5	4.5	2.5	3.5	4.5	2.5	3.5	4.5	2.5	3.5	4.5
Critical impact speed/m·s^{-1}	21.88	20.39	21.70	20.70	19.28	20.21	19.34	18.51	18.15	17.50	16.88	16.49
	21.97	20.60	20.71	20.96	19.72	20.27	17.43	18.09	17.07	15.55	15.84	16.00
	20.17	21.17	19.95	19.53	20.68	20.45	18.97	17.21	18.26	17.45	16.71	16.42
	20.49	21.61	20.87	21.25	19.01	19.34	19.55	17.59	18.01	16.27	15.76	15.70
	20.63	20.91	20.79	19.69	20.50	19.89	17.04	18.18	17.95	17.02	16.14	16.38
	20.30	21.69	20.96	20.17	20.51	19.97	17.67	18.13	16.98	17.13	16.32	16.26
	21.63	20.93	20.74	20.42	20.25	19.54	18.09	18.00	17.20	16.47	16.10	16.18
	20.57	20.90	20.53	20.31	19.36	19.54	17.70	17.86	18.03	15.60	16.02	16.75
	21.78	21.98	21.49	19.41	19.04	19.17	18.31	17.18	17.00	15.76	15.66	16.82
	22.19	20.22	20.48	20.66	20.57	20.50	18.61	18.13	16.85	15.63	16.04	16.64
	21.69	21.26	20.46	20.93	20.61	20.56	17.05	17.57	17.74	16.19	16.05	15.98
	22.11	21.50	19.81	19.54	20.60	19.86	17.48	18.31	18.05	15.70	16.57	16.14
	21.55	20.30	20.80	19.93	20.34	19.87	18.42	17.07	17.01	17.70	16.45	15.93
	20.11	21.10	20.98	21.09	19.08	19.21	17.18	18.36	17.73	16.89	16.35	15.84
	21.37	21.04	20.32	20.30	20.64	20.21	19.79	18.39	18.04	16.81	16.52	16.82
	20.49	20.33	20.46	21.11	19.63	20.37	17.77	18.18	18.23	16.52	16.23	15.87
	21.65	22.13	20.42	19.32	19.35	18.88	17.46	17.02	17.26	17.11	16.03	16.27
	20.49	20.25	21.35	19.66	18.86	19.41	18.39	17.58	17.01	16.73	16.04	16.66
	21.14	21.10	20.44	20.09	19.04	18.88	19.43	18.03	17.93	16.29	16.25	16.32
	21.50	21.89	21.79	20.58	19.59	18.93	18.43	17.83	17.56	16.01	16.52	15.85

Table 9. Critical impact speed of small granular urea impacting on target boards.

Target Material	**ABS**			**PVC**			**PMMA**			**304**		
Particle size/mm	1.5	2	2.5	1.5	2	2.5	1.5	2	2.5	1.5	2	2.5
Critical impact speed/m·s^{-1}	12.63	11.50	12.34	11.60	10.80	10.95	10.68	11.02	10.44	10.41	10.33	9.15
	12.21	11.34	12.41	11.46	11.01	11.82	10.96	10.16	10.16	10.12	10.30	10.20
	11.42	11.42	11.83	11.13	12.21	11.10	9.92	10.32	10.57	9.61	10.09	9.61
	11.59	12.18	11.93	11.65	11.13	11.53	10.21	10.88	10.71	10.32	9.94	9.96
	12.56	12.73	11.58	10.95	11.01	10.78	11.49	10.28	10.69	10.18	9.36	9.52
	12.22	12.63	11.50	11.89	11.31	10.68	11.31	10.51	10.03	10.05	10.12	9.87
	11.91	12.12	12.38	11.90	10.94	11.64	10.51	11.04	11.11	9.62	9.39	9.96
	11.78	12.54	11.27	11.65	11.53	10.86	11.55	10.12	10.59	9.55	9.79	10.20
	12.55	11.63	12.46	11.59	12.10	11.19	10.32	10.02	10.67	9.94	10.12	9.79
	12.92	12.09	12.15	11.88	11.06	10.89	10.58	11.29	10.93	10.39	9.80	9.45
	12.49	11.63	11.90	11.98	10.82	11.06	10.89	10.66	10.46	10.37	9.36	9.20
	12.31	12.37	11.37	11.64	11.16	11.51	11.30	11.01	9.94	10.24	10.18	9.78
	11.54	12.39	12.05	11.75	12.10	11.58	10.46	10.44	11.24	10.44	9.78	10.20
	12.92	11.35	11.34	10.86	11.58	10.86	10.49	9.99	10.28	9.91	9.88	9.54
	11.65	12.81	11.87	11.86	11.58	11.65	11.00	10.28	10.60	9.76	9.42	9.54
	12.10	12.41	12.42	11.50	10.86	11.13	10.30	11.16	10.99	9.57	10.67	10.28
	11.42	11.37	11.62	11.48	11.48	11.38	10.78	10.10	11.14	9.82	10.35	9.84
	12.58	12.48	11.47	11.57	11.78	11.82	11.42	11.05	10.43	10.40	9.78	9.79
	12.81	12.34	11.95	11.79	11.68	10.85	11.16	10.82	11.30	9.57	9.79	9.97
	11.58	12.21	11.38	11.13	11.63	11.57	10.47	10.79	9.95	10.47	9.81	9.93



(a) NPK compound fertilizer

(b) Organic fertilizer

(c) Large granular fertilizer

(d) Small granular fertilizer

Figure 7. Relationship between critical impact speed and fertilizer particle diameter.

Table 10. *p* value of variance analysis.

Fertilizer Variety	*p* Value			
	ABS	**PVC**	**PMMA**	**304**
NPK compound fertilizer	0.085	0.020	0.086	0.067
Organic fertilizer	0.059	0.091	0.121	0.182
Large granular urea	0.078	0.020	0.015	0.121
Small granular urea	0.133	0.037	0.309	0.079

Note: If $p > 0.05$, the effect is not significant; if $0.01 < p < 0.05$, the effect is significant; if $p < 0.01$, the effect is extremely significant.

It can be seen from Figure 7 that, generally, the critical impact speed of each variety of fertilizer decreases gradually with the increase in fertilizer granule size. The reason might be that there are some defects such as cracks and micropores in the production process of the fertilizer; the breakage of the fertilizer granules is mainly related to the accumulation of internal defects as a kind of brittle material [23,26,28,29]. The smaller the sizes of the fertilizer granules, the smaller the internal defects and the lower the density of the defects. Therefore, the overall strength of small-sized fertilizers was higher than that of large-sized fertilizers of the same variety [30,31]. However, the decrease in the critical impact speed does not increase significantly with the increase in granule size.

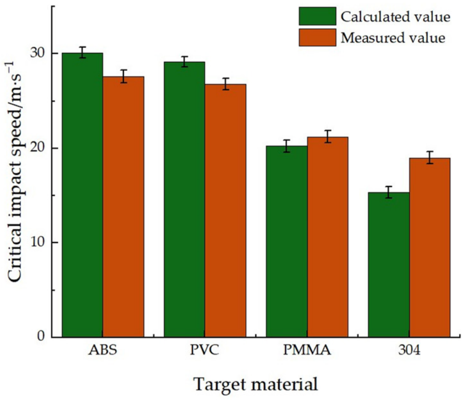
The variance analysis in Table 6 shows that the *p* values of most impact tests are greater than 0.05, indicating that, although the granule size of the fertilizer has some influence on the critical impact speed, the influence is not significant, with only 4 of all 16 treatments showing relatively significant effects of the fertilizer particle size on the critical impact speed, the NPK compound fertilizer granules impacting on the PVC board, the large granular urea on the PVC board, the large granular urea on the PMMA board, and the small granular urea on the PVC board.

It can be concluded that the critical impact speed of the same variety of fertilizer granules is independent of the granule size basically under the actual impact condition, which is consistent with the analysis results of the derived theoretical Formula (10).

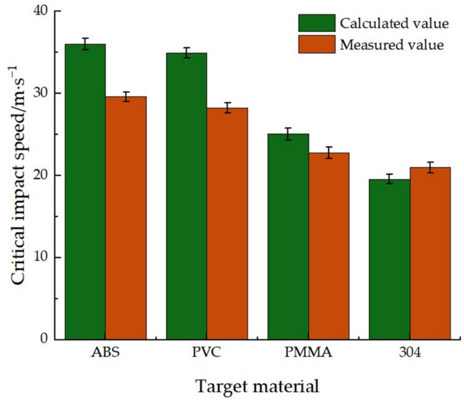
3.3.2. Comparative Analysis of Calculated and Measured Critical Impact Speeds

It can be obtained from the analysis above that the granule size of the fertilizer basically does not affect the critical impact speed. Therefore, the average value of the critical impact speed of the fertilizer granules of the same variety with different size grades impacting on a certain material target board can be taken as its critical impact speed. The comparison and analysis of the difference between the theoretical and the measured value of the critical impact speed is shown in Figure 8. It can be observed that the calculated values of the critical impact speed of the fertilizers, except small urea, are not always greater than the measured values. The calculated values of the critical impact speed are all greater than the measured values of the small urea and the reason may be related to the strain rate effect and the impact damage mechanism of the brittle materials [30,31].

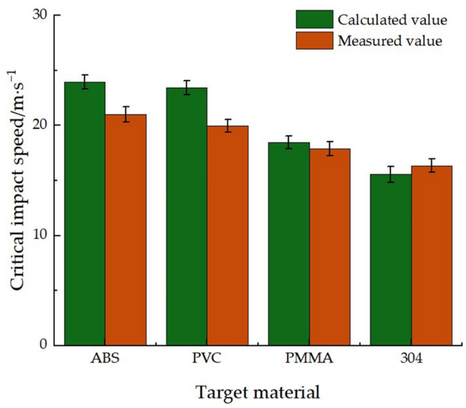
In the theoretical calculation, the fertilizer granules are assumed to be ideal elastic spheres, and the data used in the calculation are measured under static compression conditions. In fact, fertilizer granules are a kind of near-spherical brittle material; the strain rate under high-speed impact conditions would be much higher than that under a static load compression, which might increase the elastic modulus and ultimate breaking strength of the fertilizer granules [30,31]. However, under the influence of high strain, the native flaws inside the fertilizer granules are more easily activated and extended, which might reduce the strength of the fertilizer granules [25,32]. It can be concluded from Figure 8a–c that both the strain rate effect and the impact damage effect have influences on the strength of the NPK compound fertilizer, organic fertilizer, and large granular urea under the impact condition. When the impact damage plays a major role, the measured values are 3.02–19.19% lower than the calculated values; when the strain rate effect plays a major role, the measured values are 4.88~23.71% higher than the calculated values. In a comprehensive view, the impact damage effect of the three fertilizers was the main factor under the impact condition. While the small granular urea is loose and has more internal defects, and it is more vulnerable to damage under impact, it can be observed from Figure 8d that the strength of the small granular urea is always affected by impact, and the material strength greatly decreased through impact, and the measured values are only 22.03~34.95% lower than the calculated values.



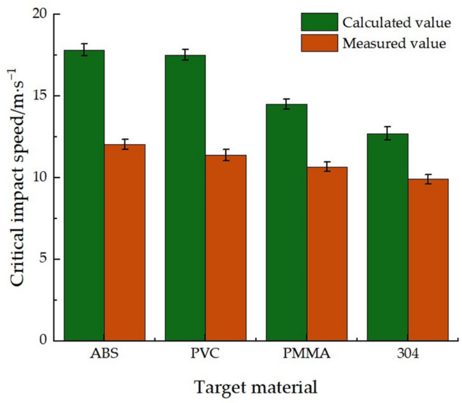
(a) Critical impact speed of NPK compound fertilizer



(b) Critical impact speed of organic fertilizer



(c) Critical impact speed of large particle urea



(d) Critical impact speed of small particle urea

Figure 8. Comparison between calculated value and measured value of critical impact speed of fertilizer particles.

3.3.3. Correction of Calculation Formula for Critical Impact Speed

It can be obtained from the above analysis that the impact failure mechanism of the fertilizer granules is complicated. Although Formula (10) can be used to calculate the critical impact speed, the accuracy still needs to improve. Therefore, based on the power function form of Formula (10), the formula for the critical impact speed was fitted with the function fitting tool of the MATLAB 2018 software, according to the data of the compression and impact tests. In the equation, $\sigma^5/\rho {E_I}^4$ is taken as the independent variable X, which describes the comprehensive properties of the two interaction materials, and the average values of the critical impact speed of the fertilizer granules as the dependent variable Y. The fitted equation is:

$$Y = 1.844X^{0.4476} \tag{12}$$

The curves of the fitted formula and theoretical formula are shown in Figure 9. The calculated fitting goodness value of the theoretical formula is 0.727, and it is 0.824 for the fitted equation, which was 13.43% higher. It proves that the calculation formula has a better applicability to the actual impact breakage of the fertilizer granules after the fitting optimization. With Formula (12), the critical impact speed of the brittle fertilizer granules could be calculated directly with the data obtained from the compression test.

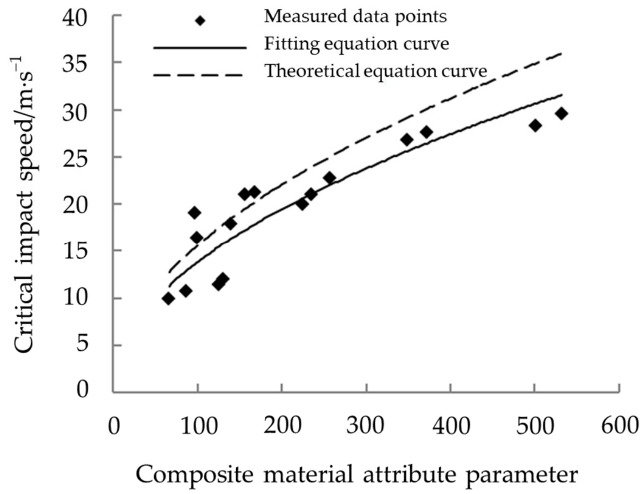


Figure 9. Comparison between fitted and theoretical equations.

4. Conclusions

(1) The four typical fertilizers are all brittle materials and can be regarded as elastomers before failure occurs. The theoretical calculated apparent elastic modulus is 233 MPa for the organic fertilizer, 208 MPa for the NPK compound fertilizer, 140 MPa for the large granular urea, and 107 MPa for the small granular urea.

(2) A theoretical impact model for the fertilizer particles was constructed based on the Hertz elastic contact theory, and the derived theoretical formula for the critical impact speed of the fertilizer granules shows the speed is only related to the material properties of the granules and target boards, and less affected by the size of the fertilizer. The test and analysis of variance give a similar result. The theoretical critical impact speed and critical stress of different types of fertilizers on different target boards are worked out based on compression test data.

(3) The comparison of the calculated and measured values of the critical impact speed shows that the theoretical calculation formula may be used to predict the critical impact speed of the fertilizer particles.

(4) The theoretical critical impact speed calculation formula is fit and corrected using the function fitting tool of the MATLAB 2018 software based on the static compression test, impact test, and theoretical impact model. The goodness value of the fitting formula was 0.824 and 13.43% higher than the theoretical equation, which could calculate the critical impact speed value of the fertilizer granules with brittle material properties more accurately and conveniently. It may provide a reference for the design of the parameters of fertilizer application machines.

Author Contributions: Conceptualization, M.X. and Y.S.; methodology, Z.J.; software, R.S.; validation, M.X. and Y.S.; formal analysis, Z.J.; investigation, H.C.; resources, B.C.; data curation, A.K.; writing—original draft preparation, Z.J.; writing—review and editing, Z.J.; visualization, M.X.; supervision, M.X.; project administration, Y.S.; funding acquisition, M.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (51975389).

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Song, X.; Dai, F.; Zhang, X.; Gao, W.; Li, X.; Zhang, F.; Zhao, W. Simulation and Experiment of Fertilizer Discharge Characteristics of Spiral Grooved Wheel with Different Working Parameters. *Sustainability* **2023**, *15*, 11309. [CrossRef]
2. Zhang, M.; Tang, Y.; Zhang, H.; Lan, H.; Niu, H. Parameter Optimization of Spiral Fertilizer Applicator Based on Artificial Neural Network. *Sustainability* **2023**, *15*, 1744. [CrossRef]
3. Xin, M.J.; Jiang, Z.W.; Chen, T.Y.; Song, Y.Q.; Wang, Y.; Huang, W.Z. Design and experiment of the fertilizer centrifugal broadcaster with guiding chute for paddy field. *Trans. Chin. Agric. Engin.* **2023**, *39*, 67–75.
4. Tang, H.; Wang, J.W.; Xu, C.S.; Zhou, W.Q.; Wang, J.F.; Wang, X. Research Progress Analysis on Key Technology of Chemical Fertilizer Reduction and Efficiency Increase. *Trans. Chin. Agric. Mach.* **2019**, *50*, 1–19.
5. Liu, Q.; Tu, W.; Pu, L.; Zhou, L. Regional Differences and Key Influencing Factors of Fertilizer Integrated Efficiency in China. *Sustainability* **2022**, *14*, 12974. [CrossRef]
6. Xiao, W.L. Design and Experiment of Precision Deep Fertilization System for Rapeseed Direct-Seeder. Ph.D. Thesis, Huazhong Agriculture University, Wuhan, China, 2023.
7. Wen, X.Y.; Yuan, H.F.; Wang, G.; Jia, H.L. Calibration Method of Friction Coefficient of Granular Fertilizer by Discrete Element Simulation. *Trans. Chin. Agric. Mach.* **2020**, *51*, 115–122, 142.
8. Lv, H. A New Kind of Method for the Optimizated Design of Outer Groove-Wheel Fertilizer Apparatuses. Ph.D. Thesis, Jilin University, Changchun, China, 2014.
9. Lei, X.; Wu, W.; Deng, X.; Li, T.; Liu, H.; Guo, J.; Li, J.; Zhu, P.; Yang, K. Determination of Material and Interaction Properties of Granular Fertilizer Particles Using DEM Simulation and Bench Testing. *Agriculture* **2023**, *13*, 1704. [CrossRef]
10. Adilet, S.; Zhao, J.; Sayakhat, N.; Chen, J.; Nikolay, Z.; Bu, L.; Sugirbayeva, Z.; Hu, G.; Marat, M.; Wang, Z. Calibration Strategy to Determine the Interaction Properties of Fertilizer Particles Using Two Laboratory Tests and DEM. *Agriculture* **2021**, *11*, 592. [CrossRef]
11. Song, X.F.; Dai, F.; Zhang, F.W.; Wang, D.M.; Liu, Y.C. Calibration of DEM models for fertilizer particles based on numerical simulations and granular experiments. *Comput. Electron. Agric.* **2023**, *204*, 107507. [CrossRef]
12. Yang, Q.L.; Li, Z.H.; Li, H.W.; He, J.; Wamh, Q.J.; Lu, C.Y. Numerical Analysis of Particle Motion in Pneumatic Centralized Fertilizer Distribution Device Based on CFD-DEM. *Trans. Chin. Agric. Mach.* **2019**, *50*, 81–89.
13. Shi, Y.; Hu, Z.; Wang, X.; Odhiambo, M.; Ding, W. Motion analysis and system response of fertilizer feed apparatus for paddy Variable-Rate fertilizer spreader. *Comput. Electron. Agric.* **2018**, *153*, 239–247.
14. Qi, X.Y.; Zhou, Z.Y.; Lin, S.Y.; Lin, L. Design of Fertilizer Spraying Device of Pneumatic Variable-rate Fertilizer Applicator for Rice Production. *Trans. Chin. Agric. Mach.* **2018**, *49* (Suppl. S1), 164–170, 180.
15. Wang, L. Design and Experiment on Broad Width and High Speed Air-Assisted Planter for Rapeseed and Wheat. Ph.D. Thesis, Huazhong Agriculture University, Wuhan, China, 2021.
16. Gao, G.B. Design and Experiment of Key Parts of Side-depth Fertilizer Device with Pneumatic Conveying for Paddy. Master's Thesis, Northeast Agricultural University, Harbin, China, 2019.
17. Zener, C. The intrinsic inelasticity of large plates. *Phys. Rev.* **1941**, *59*, 669–673. [CrossRef]
18. Wen, X.Y.; Jia, H.L.; Zhang, W.S.; Yuan, H.F.; Wang, G.; Chen, T.Y. Test of Suspension Velocity of Granular Fertilizer Based on EDEM-Fluent Coupling. *Trans. Chin. Agric. Mach.* **2020**, *51*, 69–77.
19. Fu, H. Apple Impact Bruising Mechanism and Targeted Shake-and-Catch Harvesting for Fresh Market Apples in Trellis Trained Trees. Ph.D. Thesis, China Agricultural University, Beijing, China, 2017.
20. Chi, R.Q.; Pang, B.J.; He, M.J.; Guan, G.S.; Yang, Z.Q.; Zhu, Y. Experimental investigation for deformation and fragmentation of spheres penetrating sheets at hypervelocity. *Explos. Shock. Waves* **2009**, *29*, 231–236.
21. Yi, H.S.; Xv, S.L.; Shan, J.F.; Zhang, M. Fracture characteristics of brittle granules at different loading velocities. *Explos. Shock. Waves* **2017**, *37*, 913–922.
22. Fei, H.Y.; Xv, S.L.; Tang, Z.P. Investigation on impact responses for rock-like brittle materials. *Chin. J. Rock Mech. Eng.* **2007**, *26* (Suppl. S1), 3416–3420+6.
23. Liu, K.; Zhu, Z.M.; He, L.; Xiao, D.J. Study of Crack Dynamic Propagation Law of Brittle Materials. *J. Sichuan Univ. Eng. Sci. Ed.* **2015**, *47* (Suppl. S2), 81–88.
24. Feng, X.W.; Liu, Z.F.; Chen, G.; Yao, G.W. Simulation of failure waves in glasses under shock compression. *J. Vib. Shock.* **2013**, *32*, 183–186.
25. Ye, Y.; Zeng, Y.W.; Zeng, C.; Jin, L. Experimental study on the normal restitution coefficient of granite spheres. *Chin. J. Rock Mech. Eng.* **2017**, *36*, 633–643.
26. He, S.M.; Liao, Z.W.; Liu, W.; Yan, S.X. Impact damage of granular material. *J. Vib. Shock.* **2016**, *35*, 100–105.
27. Xv, L.Z.; Li, Y.M. Critical Speed of Impact Damage on a Rice Kernel. *Trans. Chin. Agric. Mach.* **2009**, *40*, 54–57.
28. Kang, J. The 3D Numerical Simulation of Single-Particle Brittle Material Impact Breakage. Master's Thesis, Shenyang Ligong University, Shenyang, China, 2010.
29. Zheng, Z.J.; Duan, Z.P.; Zhang, L.S.; Ou, Z.C.; Huang, F.L. Contrastive Study on the Failure Mode of Glass and Ceramic under the Impact Loading. *Trans. Beijing Inst. Technol.* **2015**, *35*, 1011–1015, 1021.
30. Huang, J. Dynamic Multiscale Deformation Behavior and Particle-Breakage Properties of Granular Materials Subjected to Impact Loading. Ph.D. Thesis, University of Science and Technology of China, Hefei, China, 2016.

31. Pan, F.; Dang, F.N.; Jiao, K.; Shi, J.P. Mechanism on Enhancement of Dynamic Flexural Tensile Strength for Nonuniform Brittle Materials Under Impact Loading. *Chin. J. Rock Mech. Eng.* **2015**, *34* (Suppl. S2), 3948–3955.
32. Xiong, X. Dynamic Failure Simulations of Brittle Material Based on Discrete Element Method. Master's Thesis, Ningbo University, Ningbo, China, 2018.