# A New And Fast Method Of Evaluating Powder Energy

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**Abstract:** *In the fireworks or pyrotechnics industry, black powder (nitrate–sulphur–charcoal) is a traditional and commonly used base for creating other chemical compositions. Due to the large variety of pyrotechnic effects, the creation of such different compositions that meet so many needs has led to many different formulations. The energetic status of such formulations can easily be confused, for instance the break charge used in a breaking aerial shell can produce a tremendous audible sound like flash powder. Nowadays manufacturers may also develop their own chemical compositions by replacing and/or adding different chemical substances in order to give a "perfect" function such as large break. It is always the breaking energy that dominates the display color effect and it may generate unnecessary pressure causing danger to the operators or the audience. European standard UN default classification controls the use of metal alloys in black powder formulations, i.e. flash powder. The time/pressure test is very tedious. In the United States, the usage of flash powder is limited to 50 milligrams for ground items or 130 milligrams for aerial items for consumer fireworks. Sometimes manufacturers add non-metallic chemicals such as perchlorate and benzoate to create a formulation that can still create unnecessary pressure and cause danger. It is necessary to develop a fast and simple test method to evaluate the powder energy no matter what the chemical formulation is. Such a method can be used by manufacturing industry quality control personnel on-the-spot to evaluate the powder energy.*

*The method uses a simple test fixture which is composed of a steel tube acting as mortar and a standard "weight" steel ball. The powder energy is "evaluated" by the height to which the steel ball is ejected by the explosion of the powder confined in a standard plastic vial sitting inside the mortar. By plotting a graph of steel ball height vs amount of powder used, the graph shows a straight line with a gradient called Energy Return On Powder (EROP value). A market survey reviews powders of different chemical compositions with different EROP values.*

**Keywords:** *powder energy, black powder, flash powder, EROP value, mesh size, mortar height*

## Introduction

Black powder (chemical composition potassium nitrate : sulphur : charcoal in a ratio of approximately 60 : 25 : 15), which in Chinese is called *Hei yue*, is the base of most chemical formulations in fireworks manufacturing. Factory personnel often modify its composition by changing the percentages of these three chemical substances, replacing or substituting them with other chemical substances in order to obtain the intended effect. However the energy of the black powder will then be modified to a extent not known to the factory personnel, unless a good experienced worker might possibly be able to predict it. The only way to ensure its energy performance is to prepare a final production sample to run a test of the prototype product, so that one will know whether the powder energy is good or not. In order to provide a practical and cheaper way to "evaluate" the powder energy, we are trying to develop an alternative method for such on-the-spot factory personnel to use.

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At the same time, international requirements, including the EU and American markets, are very concerned about the usage of metal alloys mixed with black powder to make flash powder (a definition that usually means metallic chemicals added to black powder). The energy of such modified flash powder can generate a much greater effect than black powder on its own. Furthermore, due to limitations of the usage of flash powder,[1] manufacturers also invented non-metallic powder mixed with black powder which can generate similar effects to flash powder.

European authorities and experts have started to adopt the time/pressure test such as the UN Test Series 2(c)(i) time/pressure test as the definition of flash powder,[2] but the test requires expensive equipment as well as an experienced engineer to carry it out. Therefore it is not practical for on-the-spot factory personnel to follow such a time/pressure test procedure. Furthermore, a recent study[3] shows the time/pressure test is not a good reliable testing method.

## Theory

The height of the steel ball ejected from the steel tube (mortar) is directly proportional to the weight of the powder confined in the standard test vials.[4]

Among the three laws of motion of Sir Isaac Newton,[5] the second law, the Law of Momentum, is the most applicable one in this study. The law states: *If a particle is subjected to a force, the particle will accelerate. The acceleration of the particle will be in the direction of the force, and the magnitude of the acceleration will be proportional to the force and inversely proportional to the mass of the particle.* In simple terms, the acceleration of an object is proportional to the resultant force acting on it and is in the direction of this force, or

$$\text{Momentum} = mV \qquad (1)$$

For an object of mass $m$ subjected to a resultant force $F$, the law may be stated mathematically as

$$F = ma \qquad (2)$$

where $F$ denotes force in newtons; $m$, mass in Kg; and $a$, acceleration in $ms^{-2}$.

Most of the powder used in the fireworks or pyrotechnics industry uses black powder as the basis of the formulation. Its chemical reaction has been studied and can be summarized as the following reactions.

$$2KNO_3 + S + 3C = K_2S + N_2 + 3\,CO_2 + \text{Energy}$$

The energy generated evolves as a force that expands from the standard confined vial that contains a sample of black powder. The release of energy expels the steel ball from the opening of the steel tube upwards to a height, as shown in Figure 1. The ball is ejected upwards and then falls down towards the ground.[6]

Force is defined as a quantity that is capable of producing motion or a change in motion that is a change in velocity, or constant acceleration.

Force, $F = ma$,

where $F$ is the force of the ball,

$m$ is the mass of the ball,

$a$ is the acceleration of the ball.

In a more real case, the force is expressed as

$$F = ma = m(V_2 - V_1)/t \qquad (3)$$

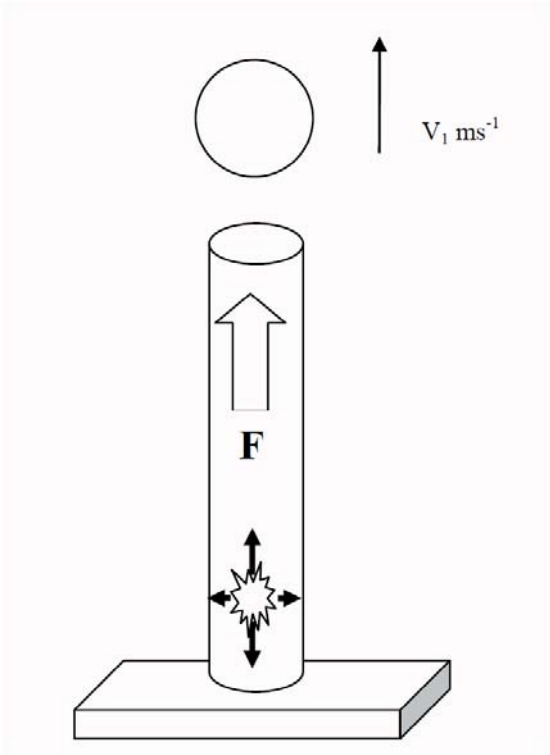


**Figure 1.** *Sketch diagram of test fixture.*

where $V_2$ is the final velocity of the ball,

$V_1$ is the initial velocity of the ball.

Therefore, $F \alpha (V_2 - V_1) \alpha$ velocity $V$.

Neglecting air resistance, an example of questions and answers is introduced by using the Equations of Motion[7] for uniformly accelerated motion that comes from elementary physics, to explain the theory, where

$V_1$ is initial velocity

$V_2$ is final velocity

$S$ is displacement

$a$ is uniform acceleration

$t$ is time of travel

(i) How high does the ball rise with velocity $V_1$?

From the equation for a free falling ball,

$$V_2^2 - V_1^2 = 2aS \quad (4)$$

$\rightarrow S = (V_2^2 - V_1^2)/2a = V_1^2 / 2 \times 9.8$,
where $V_2 = 0$ and $a = 9.8$ ms$^{-1}$

$\rightarrow S = V_1^2/19.6$

$\rightarrow S \ \alpha \ V_1^2 \ \alpha \ V_1$

(ii) How long does it take to rise up and return to ground?

From the equation for a free falling ball,

$$S = V_1 t + at^2/2 \quad (5)$$

$\rightarrow 0 = (V_1 + at/2)t$ ,

where $S = 0$,

$\rightarrow t = 0$ or $t = -2V_1/a$

The ball takes the same time to and from the ground but this is not of interest at this point.

(iii) With what speed does the ball hit the ground?

From the equation for a free falling ball,

$$V_2 = V_1 + at \quad (6)$$

$\rightarrow V_2 = V_1 + a(-2V_1/a) = V_1$

Work $W$ is defined as the transfer of energy occurring when the point of application of force $F$ newtons moves through a distance $S$ metres, with,

$W = FS$ newton metres (Nm) or joules (J)

When work is expended in accelerating a ball, mass $m$, from rest to a velocity $V$ the force $F$ being applied to give the acceleration $a$, is

$F = ma$ newtons (N)

and the distance $S$ through which the point of application moves is given by $V^2 = 2aS$. Thus the work done is

$FS = (ma)(1/2\ V^2/a) = (1/2)\ mV^2$ Nm

Energy has been transferred to the object and it is said to be have gained kinetic energy.

KE of the ball is,

$(1/2)\ mV^2$ joules (J)

When work is expended in slowly raising an object of mass $m$ through a vertical height $h$, the force $mg$ has its point of application moved through distance (or height) $h$ and so the work done is $mgh$. Energy has been transferred to the object and it is said to have gained potential energy.

PE of the ball is,

$mgh$ joules (J)

As we have seen, energy changes form one form to another, and it does so without a net loss or net gain. It is one of the most basic scientific principles.

Initial Energy = Final Energy

$$(\mathrm{KE} + \mathrm{PE})_\mathrm{I} = (\mathrm{KE} + \mathrm{PE})_\mathrm{F} \quad (7)$$

Newton's first law, the conservation of energy: Kinetic Energy and Potential Energy[8]

$$\mathrm{KE} \rightarrow \mathrm{PE}$$
$$1/2\ mV \rightarrow mgh \quad (8)$$

where $m$ is the mass of the ball,

$g$ is gravity

$h$ is the ejected height of the ball.

Assuming zero air resistance and perfect aerodynamics, therefore at the highest point,

$$\text{Total Energy} = 1/2\ (mV^2) = mgh \quad (9)$$

$\rightarrow V = \sqrt{(2g\ \Delta h)}$

When the powder generates energy and transfers it to the steel ball by ejecting it to a height, the power within the steel ball becomes,

$P = W/t = FS/t = FV$

Where **velocity, $V$ α height, $h$** because mass, $m$ and gravity, $g$ are constant for a given amount of powder used.

Power $P \alpha V \alpha h$

## Experiment

The experiment is designed to show the height of the steel ball, $m$ grams, has a relationship with the force generated by the powder confined in the steel tube. With constant mass of the ball and dimensions of the tube, it is also assumed the air resistance is neglected and experiments are therefore designed as the following parts:

I. Relationship between mesh size of black powder and height of mortar tube.

   The experiment is designed to study the different heights of stainless steel ball D, ejected by using different mesh size black powders P1, P2 and P3 with different mortar tubes T1, T2 and T3.

II. Relationship between mesh size of black powder and weight of stainless steel ball.

   The experiment is designed to study the different heights of the stainless steel ball ejected by using fixed mortar tube T2 with mesh size black powders P1, P2 and P3.

III. Relationship between weight of black powder and height of stainless steel ball

   The experiment is designed to study the effect on stainless steel ball D, ejected by using fixed mortar tube T2 with different weights of black powder P3 that was collected from a fireworks manufacturer.

IV. Relationship between weight of break charge powder and height of stainless steel ball

   The experiment is designed to study the

**Figure 2.** *Steel tube (mortar) (from left to right, A, B and C) and steel balls (shell) (from left to right, A to F).*

effect on stainless steel ball D, ejected by using fixed mortar tube T2 with different weights of break charge powder that was collected from a fireworks manufacturer.

V. Relationship between weight of flash powder and height of stainless steel ball

The experiment is designed to study the effect on stainless steel ball D, ejected by using fixed mortar tube T2 with different weights of flash powder that was collected from a fireworks manufacturer.

VI. Repeatability test using black powder

The experiment is designed to study the repeatability of the test by using black powder.

**Test apparatus**

1. Specially made steel tubes of following dimensions (length, ID), see Figure 2:

   T1 : 82.5 mm × 44 mm

   T2 : 165.0 mm × 44 mm

   T3 : 330.0 mm × 44 mm

2. Specially made stainless steel balls of following dimensions (weight, OD), see Figure 2.

   Ball A : 208 grams, 48 mm

   Ball B : 371 grams, 45 mm

   Ball C : 513 grams, 50 mm

   Ball D : 639 grams, 54 mm

   Ball E : 777 grams, 58 mm

   Ball F : 879 grams, 60 mm

3. Powders, see Figure 3.

   Black powder P1 of mesh size +40

   Black powder P2 of mesh size +60

   Black powder P3 of mesh size −120

   Break charge powder B1, mesh size −100

   Flash powder F1

4. Electrical igniter with power supply
5. Standard test vials, PP material, 5.0 ml, see Figure 4.
6. Measuring slide, 3 metres
7. Video camera

**Procedures**

1. Measure 1.0 grams of powder and place into standard test vial.
2. Place standard test vial into the bottom of mortar tube.
3. Set the stainless steel ball sitting on top of the mortar tube.
4. Fire the igniter and record the motion by video recorder.

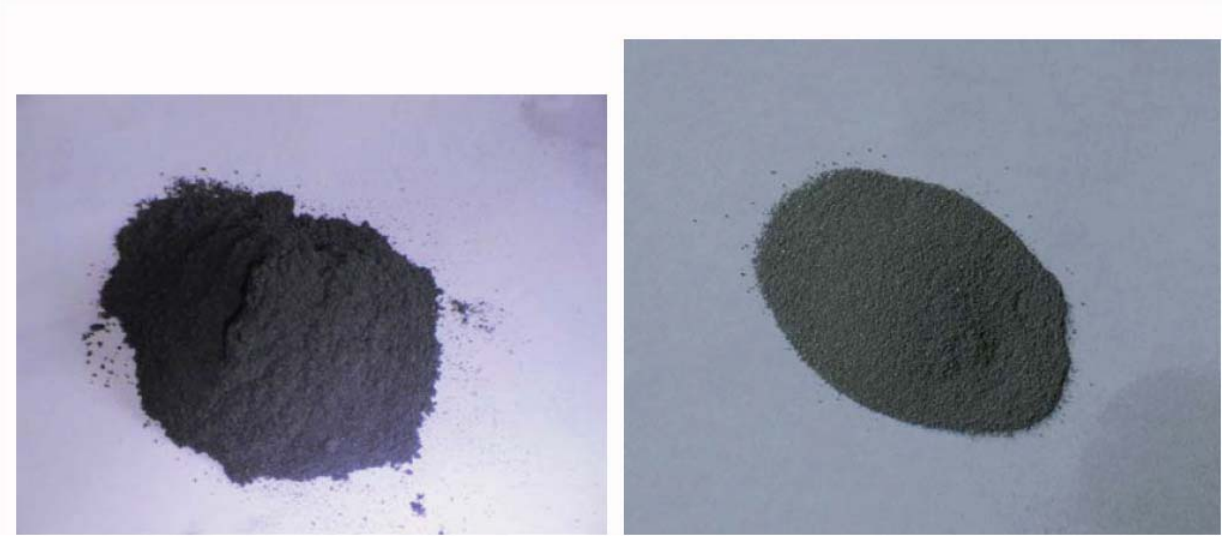

**Figure 3.** *Powders collected from market (left: break charge, right: flash powder).*

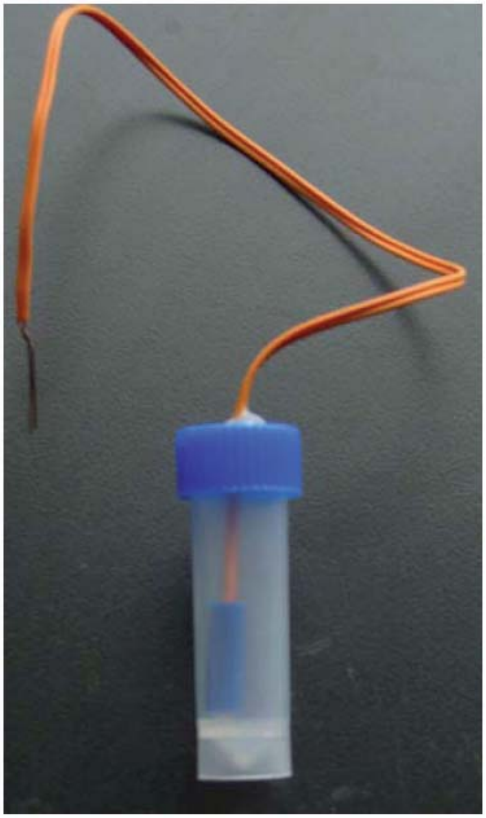

**Figure 4.** *Standard test vials with electric igniter inside.*

5. Review the video recorder to observe the height to which the stainless steel ball is ejected.

Note: All sample powders were conditioned for 24 hours in a dry chamber before use.

## Results and discussion

### I. Relationship between mesh size black powder using a steel tube and height of mortar tube

**Conditions:** 1.0 gram powder with mortars T1, T2 and T3 using ball D

**Discussion:** Black powder P1 is mesh size +40, P2 is mesh size +60 and P3 is mesh size −120. Different mesh size black powders show different energy profiles using different height mortars (Figure 5). This proves that the force generated inside the mortar tube is different which proves that the finer the powder, the higher the energy it generates and so the greater the height to which the stainless steel ball is ejected. Thus the energy generated by these three powders is

energy of P1 < energy of P2 < energy of P3

though the direct relationship of the mortar height (length), or of its internal volume, to the energy is

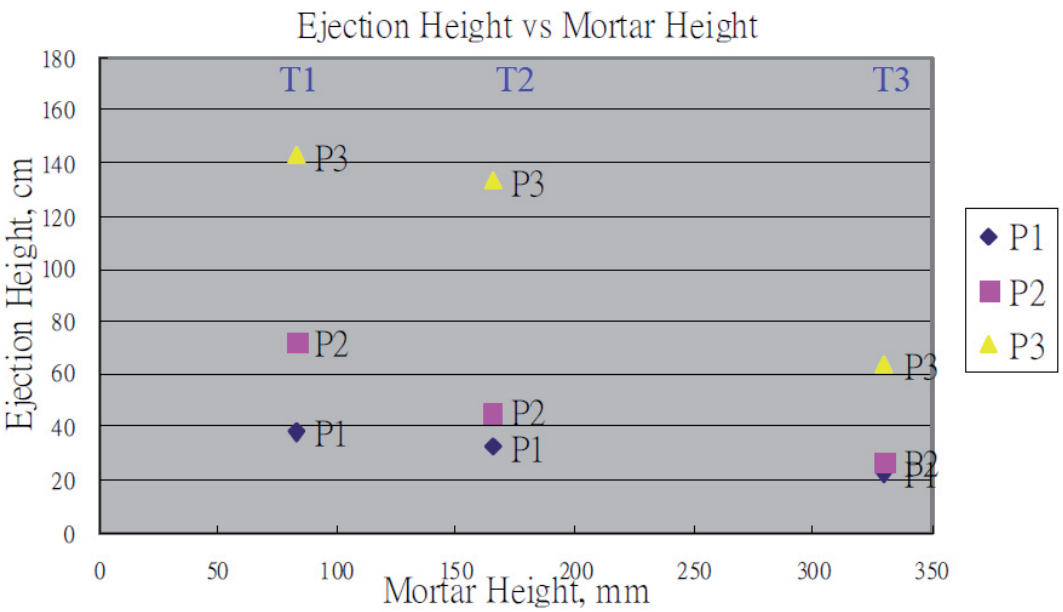


**Figure 5.** *Ejection height of steel ball from different mortar heights using different mesh size black powder.*

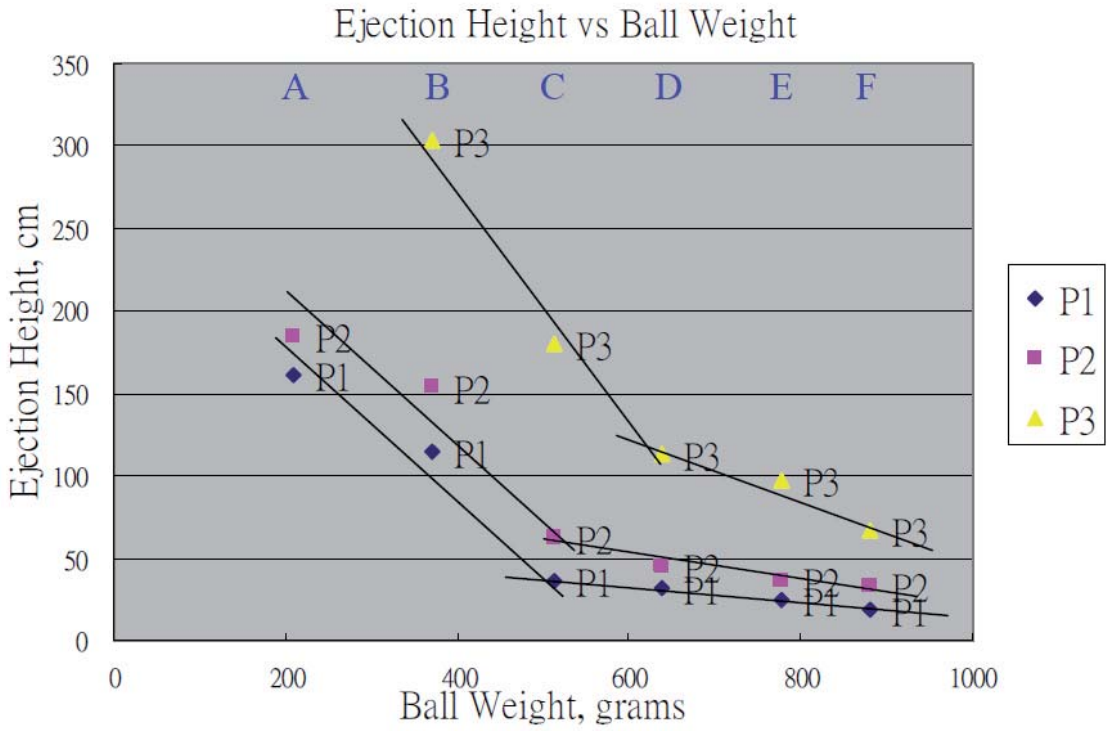


**Figure 6.** *Ejection height vs weight of steel ball using different mesh size black powder.*

unknown at this moment. However it is possible to show that the shorter the tube, the greater will be the energy transferred to the ball. Thus the energy transferred by using these three mortar tubes is,

energy transfer by T1 > energy transfer by T2 > energy transfer byT3

**II. Relationship between mesh size black powder and weight of stainless steel ball**

**Conditions:** 1.0 gram powder with mortar T2 using balls A to D.

**Discussion:**The three different curves in Figure 6 correspond to three different mesh sizes of black powder P1, P2 and P3 by using different balls (A to F). The height of ejection is inversely proportional to the ball weight, i.e. the lighter the ball the higher is the ejection.

Note: Only two points were measured for ball A because the result was too high to be recorded.

The weight of the ball is

A < B < C < D < E < F

The height to which the ball is ejected, using the same amount of powder and test conditions, is

A > B > C > D > E > F

Furthermore the diameters of the balls lie between 45 mm and 60 mm. The smallest is ball B and the biggest is ball F. Among balls C, D, E and F, the height is mostly inversely proportional to its diameter which may be caused by air resistance. To continue the study, it is appropriate to take the middle weight which is ball D for further studies.

**III. Relationship between weight of black powder P3 and height of stainless steel ball**

**Conditions:** *x* grams of powder with mortar T2 using ball D

**Discussion:** For a given amount of powder, there were three trial tests done and the height was recorded in centimetres (Table 1).

The graph (Figure 7) shows an almost linear relationship between the weight of black powder and the ejection height of the stainless steel ball. The slope of the line is 137.6 cm $g^{-1}$.

If we calculate the best fit line (Figure 8) and its

**Table 1.** *Relationship between weight of black powder P3 and height of stainless steel ball.*

| Powder weight/g | Height/cm | | | Average height/cm | Standard deviation | Relative standard deviation (%) |
|---|---|---|---|---|---|---|
| | Trial 1 | Trial 2 | Trial 3 | | | |
| 0.3 | 40 | 42 | 40 | 41 | 1.2 | 3 |
| 0.5 | 62 | 72 | 60 | 65 | 6.4 | 10 |
| 1.0 | 116 | 160 | 120 | 132 | 24.3 | 18 |
| 1.5 | 168 | 220 | 260 | 216 | 46.1 | 21 |
| 2.0 | 252 | 278 | 272 | 267 | 13.6 | 5 |

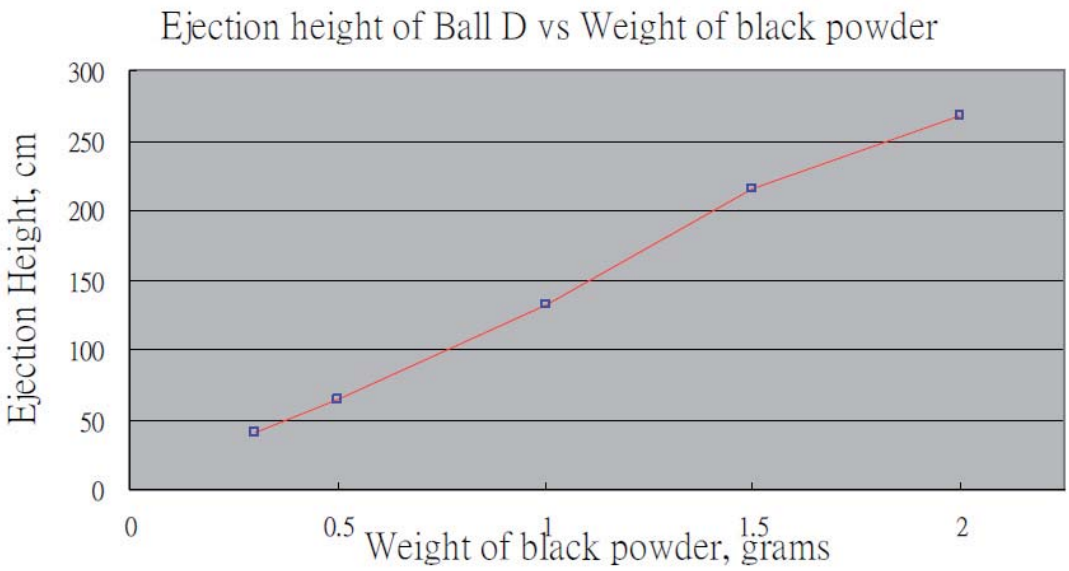


**Figure 7.** *Ejection height of ball vs weight of black powder P3, using ball D/T2*

respective energy generated by using total energy equation (9), the energies are calculated as shown in Table 2.

The slope therefore becomes energy generated by a fixed amount of powder which is here termed as Energy Return On Powder (EROP), calculated as 8.58 joules per gram (J $g^{-1}$).

**Table 2.** *Relationship between weight of black powder P3 and energy of stainless steel ball.*

| Powder weight/g | Energy/J | | | Average energy/J |
|---|---|---|---|---|
| | Trial 1 | Trial 2 | Trial 3 | |
| 0 | | | | 0 |
| 0.3 | 2.5049 | 2.6301 | 2.5049 | 2.547 |
| 0.5 | 3.8826 | 4.5088 | 3.7573 | 4.050 |
| 1.0 | 7.2642 | 10.020 | 7.5146 | 8.266 |
| 1.5 | 10.521 | 13.777 | 16.282 | 13.53 |
| 2.0 | 15.781 | 17.409 | 17.033 | 16.74 |

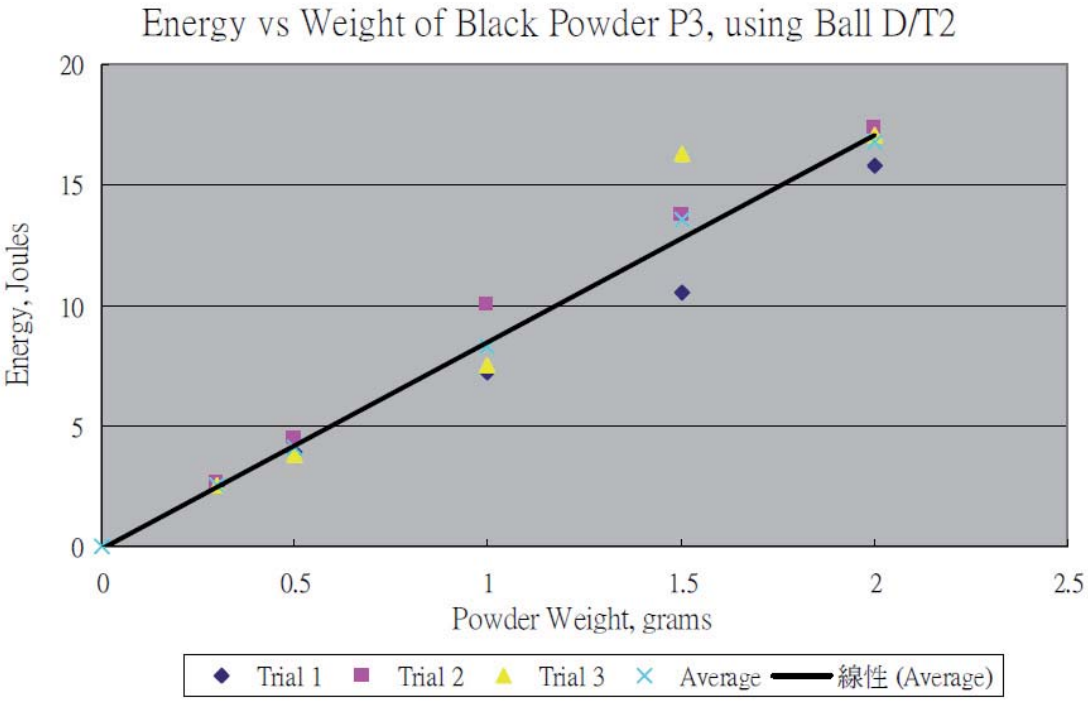


**Figure 8.** *Energy vs weight of powder P3, using ball D/T2.*

**IV. Relationship between weight of break charge powder B1 and height of stainless steel ball**

**Condition:** *x* grams of powder with mortar T2 using ball D

**Discussion:** For a given amount of powder, there were three trial tests done and the height was recorded in centimetres (Table 3).

The graph (Figure 9) shows an almost linear relationship between weight of break charge powder and ejection height of the stainless steel ball. The slope of the line is 248.0 cm $g^{-1}$.

If we calculate the best fit line (Figure 10) and its respective energy generated by using total energy equation (9), the energies are calculated as shown in Table 4.

The slope therefore becomes energy generated by a fixed amount of powder which is here termed as Energy Return On Powder (EROP), calculated as 15.53 joules per gram (J $g^{-1}$).

**V. Relationship between weight of flash powder F1 and height of stainless steel ball**

**Table 3.** *Relationship between weight of break charge powder B1 and height of stainless steel ball.*

| Powder weight/g | Height/cm | | | Average height/cm | Standard deviation | Relative standard deviation (%) |
|---|---|---|---|---|---|---|
| | Trial 1 | Trial 2 | Trial 3 | | | |
| 0 | 0 | 0 | 0 | 0 | | |
| 0.1 | 18 | 18 | 18 | 18.0 | 0.00 | 0 |
| 0.3 | 66 | 48 | 38 | 50.7 | 14.19 | 28 |
| 0.5 | 122 | 124 | 84 | 110.0 | 22.54 | 20 |
| 0.7 | 142 | 208 | 154 | 168.0 | 35.16 | 21 |
| 1.0 | 240 | 218 | 240 | 232.7 | 12.70 | 5 |

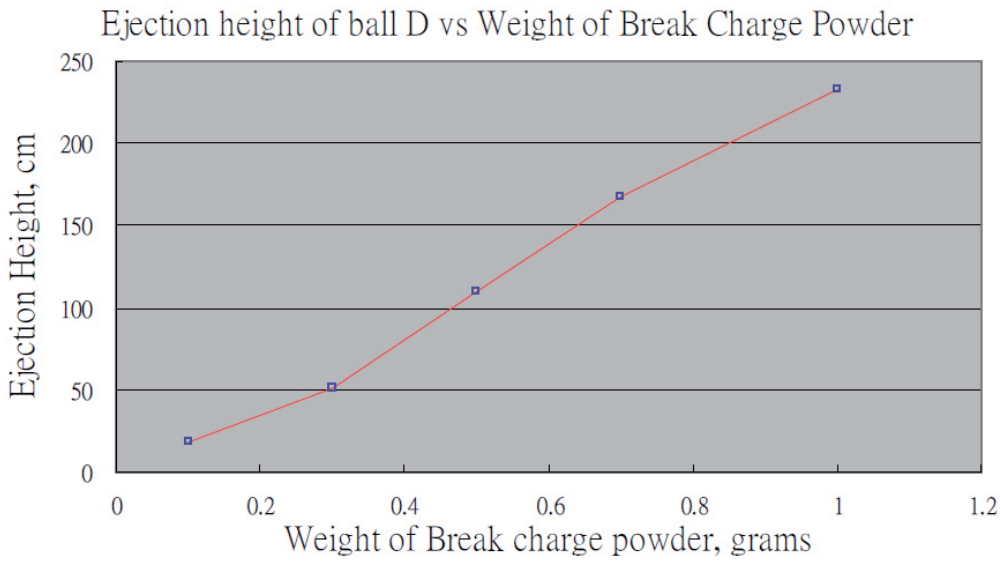


**Figure 9.** *Ejection height vs weight of break charge, using ball D/T2.*

**Table 4.** *Relationship between weight of break charge powder B1 and energy of stainless steel ball.*

| Powder weight/g | Energy/J | | | Average energy/J |
|---|---|---|---|---|
| | Trial 1 | Trial 2 | Trial 3 | |
| 0 | 0 | 0 | 0 | 0 |
| 0.1 | 1.127 | 1.127 | 1.127 | 1.127 |
| 0.3 | 4.133 | 3.006 | 2.380 | 3.173 |
| 0.5 | 7.640 | 7.765 | 5.260 | 6.888 |
| 0.7 | 8.892 | 13.025 | 9.644 | 10.52 |
| 1.0 | 15.029 | 13.652 | 15.029 | 14.57 |

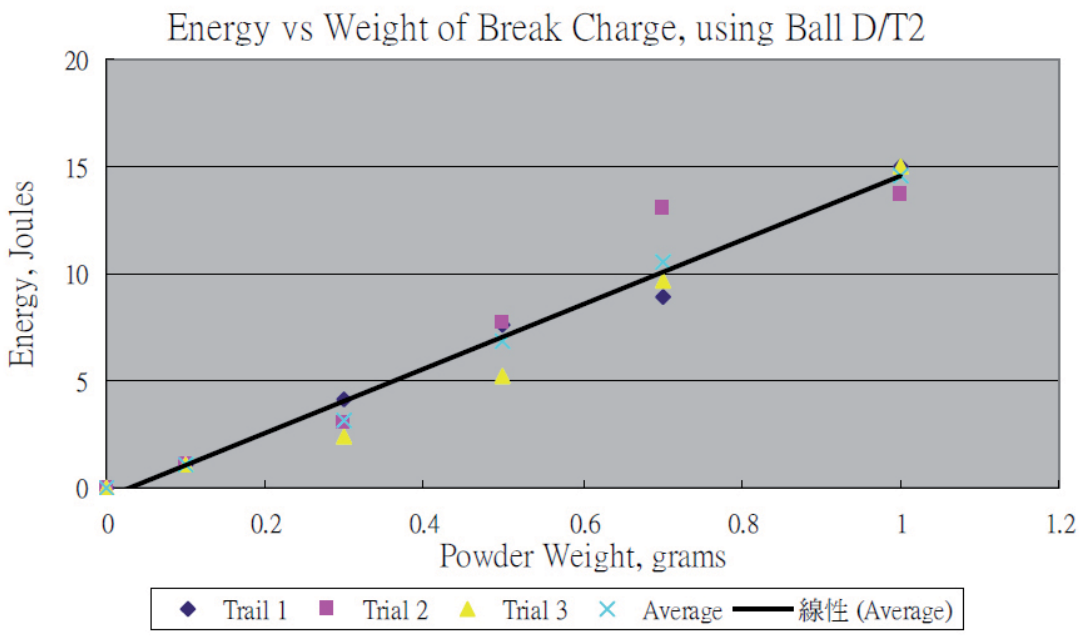


**Figure 10.** *Energy vs weight of break charge powder, using ball D/T2.*

**Table 5.** *Relationship between weight of flash powder F1 and height of stainless steel ball.*

| Powder weight/g | Height/cm | | | Average height/cm | Standard deviation | Relative standard deviation (%) |
|---|---|---|---|---|---|---|
| | Trial 1 | Trial 2 | Trial 3 | | | |
| 0 | 0 | 0 | 0 | 0 | | |
| 0.1 | 50 | 52 | 56 | 52.7 | 3.06 | 6 |
| 0.3 | 162 | 154 | 158 | 158.0 | 4.00 | 3 |
| 0.5 | 248 | 222 | 230 | 233.3 | 13.32 | 6 |
| 0.7 | 312 | 308 | 294 | 304.7 | 9.45 | 3 |
| 1.0 | 416 | 408 | 378 | 400.7 | 20.03 | 5 |

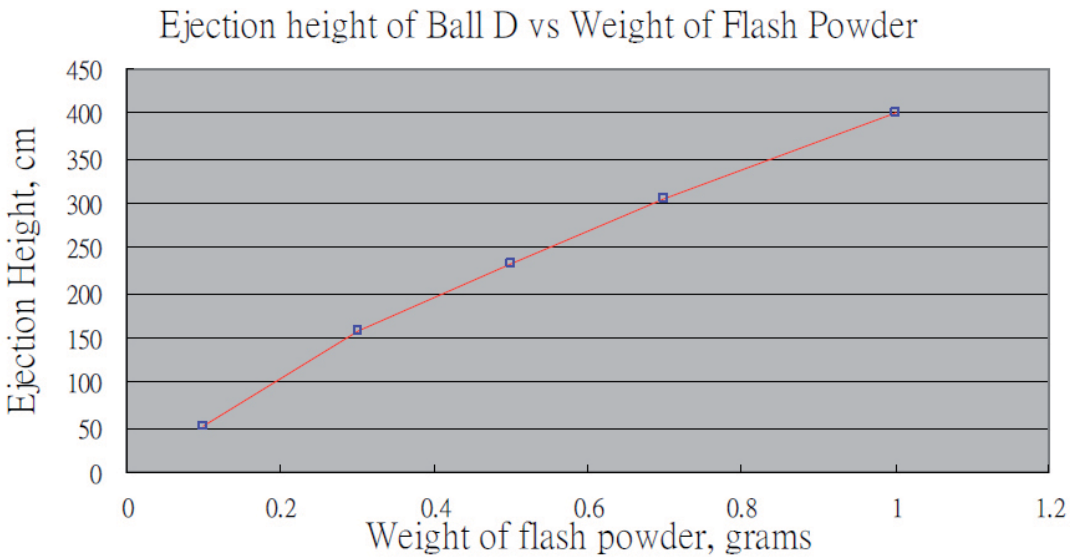


**Figure 11.** *Ejection height vs weight of flash powder, using ball D/T2.*

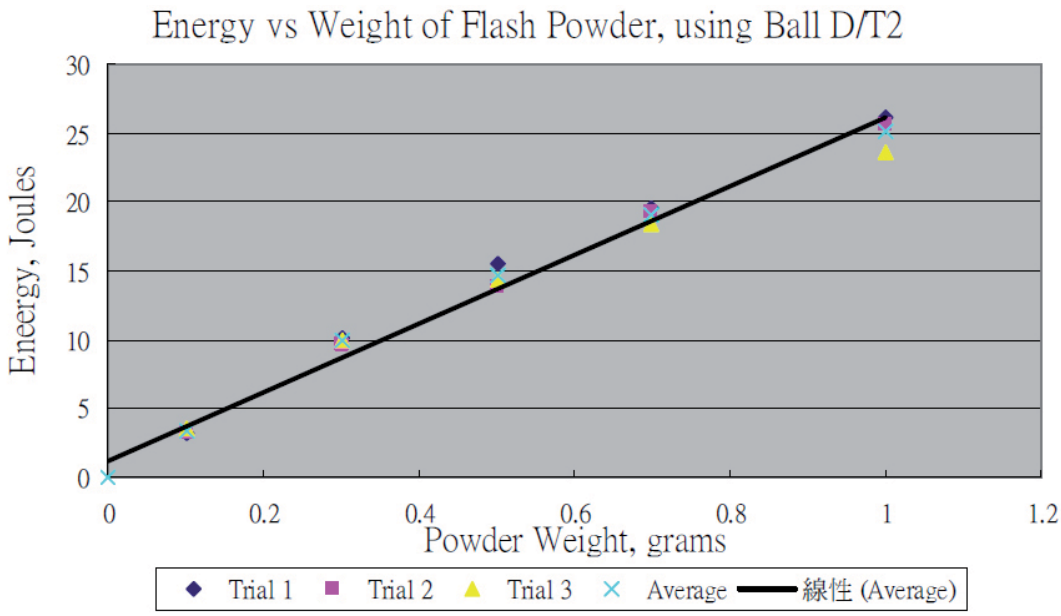


**Figure 12.** *Energy vs weight of flash powder, using ball D/T2.*

**Condition:** *x* grams of powder with mortar T2 using ball D

**Discussion:** For a given amount of powder, there were 3 trial tests done and the height was recorded in centimetres (Table 5).

The graph (Figure 11) shows another linear relationship between the weight of flash powder and the ejection height of the stainless steel ball. The slope of the line is 380.4 cm $g^{-1}$.

If we calculate the best fit line (Figure 12) and its respective energy generated by using total energy equation (9), the energies are calculated as shown in Table 6.

The slope therefore becomes the energy generated by a fixed amount of powder which is here termed as Energy Return On Powder (EROP), calculated as 23.82 joules per gram (J $g^{-1}$).

### VI. Repeatability study of black powder

**Condition:** 1.0 gram of black powder, P3 with mortar T2 using ball D

**Discussion:** The graph (Figure 13) shows 20 trial tests result with average height of 109.4 cm, standard deviation of 29.95 and relative standard deviation of 27%.

## Conclusion

The alternative method using a simple test fixture and a stainless steel ball may be used to evaluate the energy generated by the powder. The results of experiment I and II are useful in understanding

**Table 6.** *Repeatability study on black powder.*

| Powder weight/g | Trial 1 | Trial 2 | Trial 3 | Average energy/J |
|---|---|---|---|---|
| 0 | | | | 0 |
| 0.1 | 3.1311 | 3.2563 | 3.5068 | 3.298 |
| 0.3 | 10.145 | 9.6438 | 9.8943 | 9.894 |
| 0.5 | 15.530 | 13.902 | 14.403 | 14.61 |
| 0.7 | 19.538 | 19.288 | 18.411 | 19.08 |
| 1.0 | 26.051 | 25.550 | 23.671 | 25.09 |

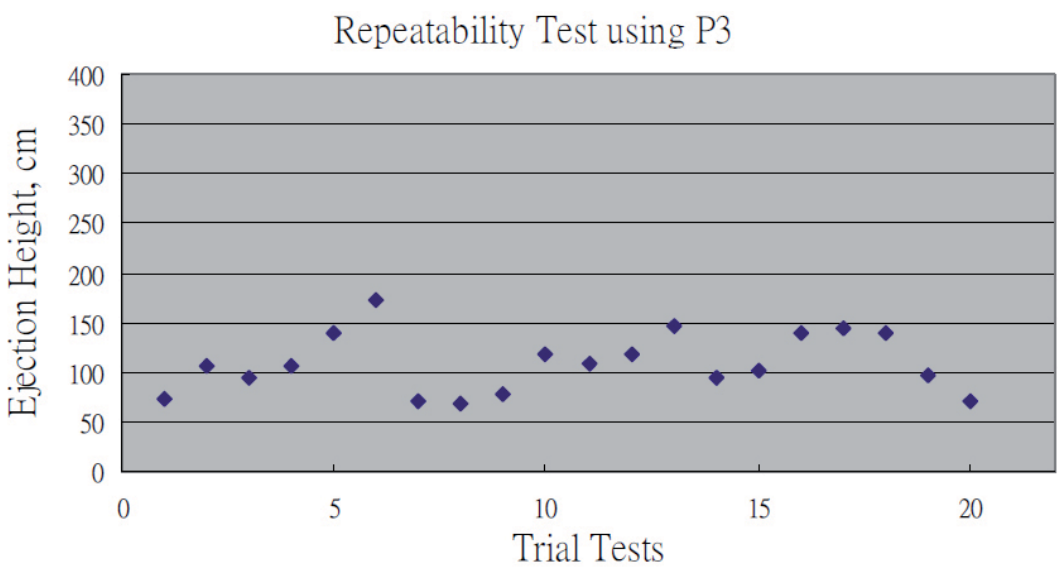


**Figure 13.** *Repeatability test of black powder P3, using ball D/T2.*

**Table 7.** *Comparison of EROP of different powders.*

| Powders | Slope of graph/ cm $g^{-1}$ | EROP/J $g^{-1}$ |
|---|---|---|
| Black powder | 137.6 | 8.58 |
| Break charge | 248.0 | 15.53 |
| Flash powder | 380.4 | 23.82 |

the effect of using mortar tubes of different dimensions and stainless steel balls of different weights. It appears that the smaller the volume of the mortar tube, the larger the energy of the powder generated. The lighter the stainless steel ball, the higher the ejection height. It is necessary that a lot of tests be performed in order to understand the relationship between the mesh size of the powder and the dimensions of the mortar tube and ball. The powder P3 shows a better proportional relationship than powders P2 and P1 with the turning point at ball D.

Experiments III, IV and V show the ejection height is directly proportional to the amount of powder used. There is a good linear relationship between the weight of powder and ejection height. All three curves show a different slope. By using the linear equation, integrating these three curves will produce a slope factor of 137.6 cm $g^{-1}$, 248.0 cm $g^{-1}$, and 380.4 cm $g^{-1}$. The higher the figure is, the higher the energy. In an alternative expression for the energy generated by different powders under these test conditions with the standard test fixture, we can use

$$PE = mgh$$

$$EROP = PE/\text{mass of powder} \qquad (10)$$

The method is very simple and practical for non-technical personnel to evaluate the amount of energy stored in the powder. By using this principle, we have a good practical technique to separate those powerful formulated powders from traditional black powder formulations. The different slopes of different powders generate different EROP values, from equation (10), calculated and shown in Table 7. These index values are a good indication of energy produced by the powders.

Following the experiment, several samples were collected from the market and tested. The results are listed as Table 8.

The EROP is a good index value and shows that black powder lies below 10 J $g^{-1}$. Break charges lie between 10 and 20 J $g^{-1}$. There are some exceptions because of its wide usage in the industry, depending whether it is used in breaking shells or breaking insert tubes. Flash powder is the most powerful among these three types of powder,

**Table 8.** *Comparison of EROP of different brands of powders.*

| Powders | | Mesh Size | EROP/J $g^{-1}$ |
|---|---|---|---|
| Formulation | Source | | |
| Black powder | (Brand A) | −120 | 6.8 |
| | (Brand B) | −120 | 6.9 |
| | (Brand C) | −120 | 5.5 |
| | (Brand B) | 60 | 4.6 |
| | (Brand B) | 40 | 3.7 |
| | Unknown | Unknown | 8.6 |
| Break charge | (Brand QC) | Unknown | 4.4 |
| | (Brand DS) | Unknown | 14.3 |
| | Unknown | Unknown | 15.5 |
| Flash powder | (Brand EZ) | Unknown | 14.0 |
| | (Brand HB) | Unknown | 26.1 |
| | Unknown | Unknown | 23.8 |

and the EROP values lie between 20 and 30 J $g^{-1}$.

Further study is still required in order to better describe the energy level by using this alternative evaluation method. Such studies should also extend to consider air resistance, mortar volume etc.

## References


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