Assessment and Classification of British PE4 Plastic Explosive: Impacts, Risks, and Military Applications in the Malaysian Context

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***Abstract*— Plastic explosives are produced in different countries and regions under different categories and applications. The British Plastic Explosive (PE4) is composed of 88 per cent Royal Demolition Explosive (RDX) mixed and 12 per cent of plasticizer compound and has "nearly identical" explosive qualities to Composition C-4 (C-4). This paper briefly reviews a British PE4 used in the explosion, demolition, and blast test activities. This activity has been held by military personnel, enforcement agency, and experts to accomplish their interests. The main purpose of this study is to discuss the use of plastic explosive PE4 in a research and development project, as well as the evolution of the PE4 production industry in military explosion classification. The novelty of this research is a considerable risk that the explosion standard will vary owing to the tropical impacts in Malaysia. Furthermore, to date, there has been little interest in exploring Malaysian military assets, logistics, and military equipment in terms of capabilities and preparedness. In addition, these findings will be of interest to developing a military explosive performance model using computer design such as an artificial neural network.**

Keywords*— *Plastic explosive PE4; military explosion; tropical Malaysia

I. Introduction

Over the past decade, numerous scientists and researchers used a variety of approaches to investigate the military plastic explosive's effect on the shelf life and stability of the product. Nowadays, plastic explosives are produced by many companies in different countries and regions and are commercially available under different categories and applications (Elbeih et al., 2019). Several studies have examined the sensitivity and performance of plastic materials available in the market (Agrawal, 2010; Elbeih et al., 2019; Licht, 2000). To minimise the explosive's sensitivity and improve its mechanical qualities, the plastic explosive principally comprises energetic material as a filler connected by a rubbery substance of preference (Elbeih et al., 2019). Currently, the well-known plastic explosive PE4, imported from Europe, is broadly used by the Malaysian Armed Forces (MAF) in military training (Provatas, 2000). Due to the widespread use of British PE4 in explosion, demolition, and blast testing activities (Ahmad et al., 2008), the authority has imposed Rules and Regulations specifically for PE4 usage as well as Standard Operation Procedures (SOP) in military drills.

This study briefly reviews a British PE4 used in the explosion, demolition, and blast test activities. This activity has been held by military personnel, enforcement agencies, and experts to accomplish their interests. The purpose of this study is to discuss the use of plastic explosive PE4 in a research and development project, as well as the evolution of the PE4 production industry in military explosion classification. It is thought that (Abdul Rahim et al., 2020; Razak & Alias, 2021) conducted research studies on equivalence blast testing to assess the explosion performance of plastic explosive, PE4, especially at a designated location in Malaysia.

The novelty of this research is a considerable risk that the explosion standard will vary owing to the tropical impacts in Malaysia, as well as PE4 being imported directly from Europe. A daunting task for military personnel and local university researchers in defense and security clusters, the likelihood of the explosion performance is far from the standard if proactive action is not yet taken in tropical studies. Additionally, this study briefly describes a manufacturer of plastic explosive PE4 for military explosives.

This study also discusses the significant challenge faced by researchers due to insufficient literature review and argumentation regarding the topic of plastic explosive PE4 utilisation in Malaysia, as well as its application in the Malaysian Armed Forces (MAF) training routine. Furthermore, to date, there has been little interest in exploring Malaysian military assets, logistics, and military equipment in terms of capabilities and preparedness.

A. Introduction to Explosive

Explosives have been utilised for over a thousand years as well as the ancient Chinese developed early missiles and firecrackers using a crude form of black powder (Davis, 1998). During the Renaissance, explosives were utilised to boost quarrying yields and black powder was the primer propellant for early muskets and cannons. Explosive research and manufacture require adequate fundamental knowledge and understanding of their related properties.

The researcher spent a significant amount of time conducting experiments to determine and specify the properties of every explosive material, such as detonation velocity, detonation rate, and detonation pressure. Because explosives are chemically reactive, they can detonate under certain conditions (Pisharath et al., 2022). Thus, to minimize the risk of explosive tests, it is vital to have a general grasp of the approximate range of parameters for each explosive material, before the experiment.

B. Explosive Materials and Classification

High explosives are used in a wide variety of applications, including mining and quarrying, building, seismology, and petrogeology (Perry et al., 2008). Primary and secondary explosives for the high explosives category are classified by their explosive's sensitivity to energy input (Goodpaster, 2019). Primary explosives such as lead azide or mercury fulminate are extremely sensitive to small energy inputs on friction, shock, or static electricity (Lee, 1998). A small amount of energy input causes a shock wave to propagate through the unreacted explosive. Due to the high sensitivity of primary explosives, they are typically not handled until they are placed in blasting caps and detonators (Lee, 1998).

Secondary explosives are employed in various applications, including blasting caps and sensitising blasting agents (Perry et al., 2008). Secondary explosives detonate more quickly and produce a larger amount of energy than primary explosives. However, they require more energy input to start the explosion. Figure 1 shows the types and applications of explosives.

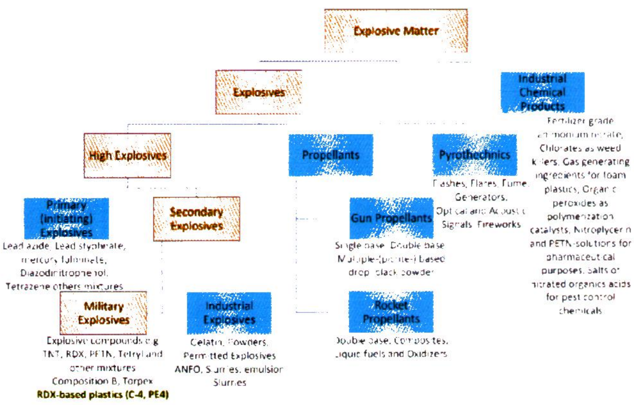

Figure 1: Explosive materials and their application

Military explosives and industrial explosives are classified under secondary explosives. From Figure 1 (Meyer et al., 2016), examples of military explosives compounds that are regularly used are Trinitrotoluene (TNT), Royal Demolition Explosive (RDX), Pentaerythritol Tetranitrate (PETN), Tetryl, Composition B, Torpex as well as RDX-based plastics such as Composition C-4 and Plastic Explosive PE4. The military explosive is powerful but safe and easy to handle, as well as can only be detonated if it meets specified conditions (Mathieu & Stucki, 2004).

The main parameter used to categorise an explosive is the detonation velocity. The other key parameter is whether or not the explosive can be ignited using a standard detonator (Lee, 1998). Military explosive is a type of high explosive with a velocity of detonation of greater than 7000 meters per second (m/s) (Zapata & García-Ruiz, 2021). TNT, PETN, High Melting Explosive (HMX), Semtex, and PE4 are all examples of these explosive compounds (Alexander, 2011). However, for industrial explosives such as commercial explosive compounds, a detonation velocity of between 2000 (Huang et al., 2012; Zlobin et al., 2014) and 7000 meters per second (m/s) has been measured (Thurman, 2017). Meanwhile, a detonation velocity measured as less than 2000 meters per second (m/s) is classified as low explosives. Low explosives include gunpowder, fireworks, and cordite (Meyer et al., 2016).

C. Explosive by Its Structure

The explosives found in major organic structural groupings will be defined in this section. The section describes what these explosives are, how they are created, and how they are utilised. There are two types of explosives: organic and inorganic explosives (Zapata & García-Ruiz, 2021). This topic will focus on organic explosives, with a few inorganic explosives being explored separately in the future. (Cooper, 1977) draws an explosive organisational arrangement, as shown in Figure 2.

Organic explosives contain two types of explosive compounds: aromatic and aliphatic explosive compounds (Zapata & García-Ruiz, 2021). In general, aromatic nitro compounds are produced via direct nitration with nitric acid, which is often mixed with sulfuric acid. The nitronium ion $(NO2)+$ attacks the ring first, resulting in the nitration process. According to (Cooper, 1977), aliphatic organic compounds are divided into alkane, alkene, and alkyne. Aliphatic explosives are made up of open-chain aliphatic and cycloaliphatic groups. In most aliphatic explosives, the nitrate ester group (-ONO2) and the nitramine group (-NH -NO2) are the main sources of oxidiser. Furthermore, mixed acid nitration of organic alcohol is commonly used to create nitrate esters

D. Use Forms of Explosives

Pure explosive compounds are sometimes used in their pure state as liquids, pressed powders, or castings. However, the majority of explosives deployment needs mechanical properties, where they are mixed with other explosives and other inert materials to modify mechanical properties, thermal, output, or sensitivity capabilities. The resulting mixtures can then be used in a variety of ways to produce specific explosives, which are listed in Figure 2 (Cooper, 1977). Plastic bonded machined and putties are the only two topics of used forms of explosives that are discovered and described in this paper. In the world of plastic explosives, these two have a lot in common.

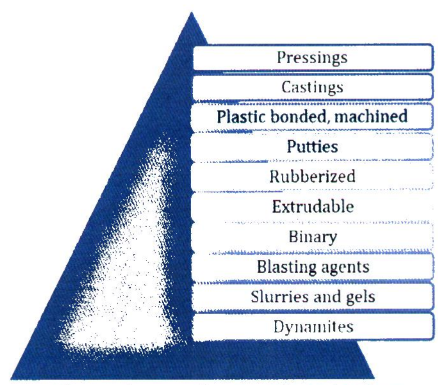

Figure 2: Use forms of explosives

The PBXs are powdered explosives with additional plastic binders. During the preparation stage, the binder is normally precipitated out of the solution to coat the explosive crystals. Agglomerates-coated crystals form pressing "beads." The beads are then die-pressed or isostatically pressed at temperatures of up to 1200 degrees Celsius. Then, at pressures ranging from 1 to 20 kpsi, pellets or billets with densities up to 97% of the theoretical maximum density (TMD) are produced (Baer et al., 2007). The billets produced in this method are highly strong mechanically and may be machined to extremely close tolerances.

Putties are composed of finely powdered RDX and plasticizers. The mixture does have a putty-like consistency and may be easily shaped by hand into any desired shape. Like modelling clay, it maintains its shape when moulded. Although other additional putty compositions have been discovered, only one is currently commonly utilised in the United States, which is Composition C-4 and made up of the following formulation as shown in Table 1.

TABLE I. CHEMICAL COMPOSITION OF C-4

Component	Percent (weight)
RDX	91.0
Di(2-ethylhexyl) sebacate	5.3
Polyisobutylene	2.1
20-weight motor oil	1.6
Total	**100.0**

The British military uses a similar formulation named PE4. This mixture contains approximately 88 per cent RDX and about 12 per cent plasticizer (Elbeih et al., 2013, 2019). Nowadays, the Malaysian Armed Forces utilise this PE4 as the main explosive material in their military explosion activities (Provatas, 2000). According to (Chick & Learmonth, 1985), PE4 is made up using this formulation as shown in Table 2.

TABLE II. CHEMICAL COMPOSITION OF PE4

Component	Percent (weight)
RDX	88.0
Pentaerythritol dioleate	1.0
DG-29 lithium grease (Lithium stearate)	2.2
DG-29 lithium grease (Mineral oil BP)	8.8
Total	**100.0**

II. LITERATURE REVIEW

A. *Plastic Explosive Producing Countries*

Plastic explosive chemicals, such as cocaine and its derivatives, require neutron inspection when encased in heavy metals such as steel and lead (Ferreira et al., 2010). Several researchers examined the decomposition kinetics of plastic explosives produced by various countries, as well as their impact on the shelf life and stability of various goods, using diverse methodologies. Previous research works and publications compared the sensitivity and performance of commercially available plastic explosives and provided information on various types of plastic explosives (Elbeih et al., 2019; Zeman & Jungová, 2016). Thus, here is the list of various types of plastic explosives and details of the producing countries in Table 3.

TABLE III. VARIOUS TYPES OF PLASTIC EXPLOSIVES AND THEIR PRODUCING COUNTRIES

Explosive Name	Country	Regions	References
PE4, PE4-MC	Australia	Oceania	(Australian Munitions, 2020; Glass, 2018; Thales, 2010)
Semtex-1H (orange-coloured), Semtex 1A (red-coloured), Semtex 10 (also called Pl Np 10; black-coloured), Pl Hx 30 (gray-coloured)	Czech Republic	Europe and Northern America	(Sheela A, 2020)
C3, C-4	Greece	Europe and Northern America	(Pichtel, 2011; Sheela A, 2020)
PVV-5A Plastic Explosive	Russia	Europe and Northern America	(Pichtel, 2011; Sheela A, 2020)
Ministry of Defense (MOD) explosives PE2, PE3A, PE4, SX2, PE7, PE8, SX4, DPX, DPX1, DPX9 *Non-MOD explosives* Composition C-4, M5A1 and M112 charges produced by Mondial Defence Systems), Semtex, PW4	United Kingdom	Europe and Northern America	(Pichtel, 2011; Sheela A, 2020)
Composition C-4	USA	Europe and Northern America	(Pichtel, 2011; Sheela A, 2020)
PP-01 (Composition C-4 equivalent)	Yugoslavia /Serbia	Europe and Northern America	(Pichtel, 2011; Sheela A, 2020)

What is interesting in Table 3 is the dominance of the European and Northern American regions in producing plastic explosives. A total of 6 European countries are the main producers of plastic explosives supplied to their users worldwide, following one from Oceania. It is almost certain that plastic explosive product specifications in the military world refer to European standards.

B. *Military Plastic Explosive PE4*

Military explosives are the combination of energetic organic materials such as HMX (1,3,5,7-tetranitro-1,3,5,7-tetrazacyclooctane), RDX (hexahydro1,3,5-trinitro-1,3,5-triazine) and TNT (trinitrotoluene), along with binders and other additives (Hoek, 2004). PE4 is a composition of RDX explosives, a plastic binder, and a plasticizer (Chick & Learmonth, 1985). PE4 material has an explosive charge that is nearly identical to C-4 explosive. The PE4 charge in use has a detonation velocity of 7,900 m/s (Choi et al., 2014).

C. *Plastic Explosive PE4 Composition*

According to (Mondial Defence Systems Ltd, 2014), the British PE4 (UK standard) consists of 88.0% RDX, 1.0% pentaerythrite di-oleate and 11.0% DG-29 lithium grease (corresponding to 2.2% lithium stearate and 8.8% mineral oil BP) as the binder; a taggant (2,3-dinitro-2,3-dimethylbutane, DMNB) is added at a minimum of 0.10% weight of the plastic explosive, typically at 1.0% mass. The British PE4 is composed of RDX mixed and a plasticizer, with the percentage of RDX is 88 per cent and the plasticizing compound is 12 per cent (Thurman, 2017). In most situations, PE4 is described as having "nearly identical" or "very similar" explosive qualities as Composition C-4 in its explosive properties (Bogosian et al., 2016).

The British military used a similar formulation of Composition C-4 and named it PE4. This mixture contains approximately 88 per cent RDX and about 12 per cent plasticizer. Nowadays, the Malaysian Armed Forces utilize this PE4 as the main explosive material in their military explosion activities. PE4's major ingredients are cyclonite, paraffin, and a bonding agent, whereas C-4 is composed primarily of cyclonite 9176, which is mixed with polyisobutylene 2.1 per cent, motor oil 1.6 per cent, and di-(Zethyl-hexyl) sebacate 5.3 per cent (Campbell & Chapman, 2008).

Based on the manufacture datasheet (Mondial Defence Systems Ltd, 2014), the explosive shall consist essentially of RDX Grade 102 uniformly coated with PE4 plasticizer in the form of a homogeneous whitish dough, free from foreign matter and visible impurities. A description of commercial product specifications is as follows in Table 4. PE4 is a conventional plastic explosive, widely used for the production of improved energetic systems for defensive and offensive use. PE4 is RDX-based and is available in the cartridge as shown in Figure 4 and in bulk form. The explosive component PE4 (British) is white in colour identified by distinctive standard colour (Bogosian et al., 2016).

III. PE4 Product Establishment

A. PE4 Industry Manufacturer

Turning to this topic, there are only two countries that produce Plastic Explosive (PE4) for high explosion usage. The first country which produces and supplies PE4 around the world is the United Kingdom. United Kindom PE4 is generally white in colour and has a similar consistency to putty explosive, free from solid impurities. This PE4 has been produced by the Ministry of Defense, United Kingdom. This high explosive product standard has been established and controlled by the Ministry of Defense, United Kingdom, and Mondial Defence Systems. The formulated ingredients consist of 87+2% RDX, 13+2% binder, and informative plasticity (Tyas, 2019). The detonation velocity for the PE4 is 8,000 m/s (Mondial Defence Systems Ltd, 2014).

In 2012, UK PE4 was designed, developed, and manufactured by Primetake Ltd, a company located in Lincoln, United Kingdom (Primetake Ltd, 2012). This company takes the initiative to set high explosive performance and safety for PE4 according to Ammunition and Explosives Regulations dated December 1993. During normal training, battle inoculation charges should not exceed 1kg of PE4 (Ministry of Defence (MoD) U.K, 2006) thus, the safety distances in metres start from 235m. The market for UK's PE4 products is the Ministry of Defence, United Kingdom, the international defence forces including the Malaysian Armed Forces, and commercial customers.

The second country which produces and supplies PE4 around the world is Australia. Australian PE4 is a white and soft plastic explosive to be used for demolition and explosive ordnance disposal (Chick & Learmonth, 1985). This PE4 is formulated in the United Kingdom and is produced by the Australian government. The formulated ingredients consist of 88% RDX grade B, which is boiled and milled, 11% plasticizer, and 1 % of Pentaerythritol dioleate (Chick & Learmonth, 1985). The product development and product specification were verified and approved for public release by the Department of Defence, Defence Science and Technology Organisation, Melbourne, Australia, in 1986. According to (Chick & Learmonth, 1985), the detonation velocity for the PE4 at the density of 1.59 Mg/m3 is recorded at 8,027 m/s.

Australia PE4 has been produced for mass production by Thales Australia company. This high explosive product standard needs to meet a requirement from the Australian Defence Force (ADF). Hence, this product is manufactured at Thales Australia's Mulwala, a mass product specification based on code DEF (AUST) 5615B, and the basic route spec is DEF STAN 07-10 (UK) (Thales, 2010). There is some evidence that PE4 from Australia still refers to European standards, which are based on the United Kingdom standard. The potential market for Australia's PE4 products is the Australian Defence Force, the international defence forces, and commercial customers.

B. PE4 Utilisation: Issues and Challenges

In this section, we discussed significant challenges to PE4 deployment, particularly those related to research and development projects and end-user input. Several challenges of PE4 included difficulties in manpower management during the PE4 explosion session, the past studies and research activities neglecting tropical assessments, the industry maker excluding tropical testing, as well as a lack of argument for PE4 research. The Malaysian government works hard every year to restore the economy by cutting operating costs (Hirnissa & Baharom, 2009; Wan Farisan et al., 2017). Defense budgets also have no exception, even when it involve national security preparations (Aye et al., 2014). Over the decade, British PE4 has been widely used by the Malaysian Armed Forces in their military training and demolition activities (Ahmad et al., 2008; Provatas, 2000). As a result of the tropical effects in Malaysia, the explosion performance standard and capabilities may differ.

To date, no Tropical Standards have been developed for British PE4 explosives. One of the most obvious possibilities is that erroneous explosion tests have been performed as a result of tropical effects when compared to the Standard provided. Furthermore, there is currently no research or guidelines that take into account tropical elements; thus, there is a significant risk that an explosion will have a direct impact or cause injuries.

C. Prior Research Activity Neglecting Tropical Measurement

The following Table 4 shows a list of research studies and activities that have been deploying British PE4 as an explosive material in explosion and blast tests, regardless of tropical conditions. It was discovered that the parameter measurements for tropical elements, especially environment humidity and temperature, were not recorded.

TABLE IV. PE4 Research and Development

Authors	**Role of PE4**	**Methodology** (Experiment / Simulation)	**Tropical measurement**
(Sadat Nasiri et al., 2022)	PE4 is used as an explosive component	Field Experiment	No measurement
(Razak & Alias, 2021)	PE4 is used for blast load test	Field Experiment	No measurement
(S. Rigby et al., 2020)	PE4 is used for the explosive blasts test.	Experiment	No measurement
(Langdon et al., 2020)	PE4 is used as an explosive component only	Field Experiment	No measurement

(Abdul Rahim et al., 2020)	PE4 is used to test the behaviour of the charges after detonation	Experiment	No measurement
(Sharma et al., 2017)	PE4 is used for blast load	Numerical Simulation	No measurement
(Bogosian et al., 2016)	PE4 is used in the equivalent test	Simulation	No measurement
(S. E. Rigby & Sielicki, 2015)	PE4 is used in the equivalent test	Field Experiment and Numerical Simulation	No measurement

D. PE4 Europe Industry

Table 5 shows country temperature information for PE4 producing countries, including average temperature data, coldest temperature data, and hottest temperature starting from the year 1991 to 2020. This informative data is obtained from the United Nations Climate Change Knowledge Portal (for Development Practitioners and Policy Makers). Table 5 also includes information on Malaysia as a baseline for a tropical country. This comparative table is about finding the gap in a tropical element between PE4 product manufacturers and PE4 end-user, especially the Malaysian Armed Forces.

TABLE V. CLIMATE CHANGE KNOWLEDGE INFORMATION

Country or Region	**Average Temperature (1991-2020) (°C)**	**Coldest Temperature Month (1991-2020) (°C)**	**Hottest Temperature Month (1991-2020) (°C)**
Australia / Oceania	21.94	13.20	29.90
United Kingdom / Europe	9.07	0.10	17.20
Benchmark (as PE4 user)			
Malaysia / Asia	25.75	24.50	27.20

The most surprising aspect of the data in Table 5 is that the United Kingdom produces PE4 plastic explosives reflecting their own country temperature only and not considering the country of the tropical region like Malaysia. Generally, the standardisation of products and development criteria has met the needs of the country despite not taking into account the needs of consumers such as Malaysia, especially the Malaysian Armed Forces. Furthermore, during PE4 product development and mass production, quality assurance and quality control testing must consider the actual tropical environment.

The most likely problem with PE4 use in Malaysia seems to be that the explosion performance measurement is inaccurate when compared to the standard. Thus, there has been little conflict in exploring Malaysian military assets and equipment in terms of capabilities and preparedness. In addition, (Fleming et al., 2016) notes that research into the sources of insecurity posed by global environmental degradation points to Africa, Asia, and the Americas as the most likely future hotspots. According to (Fleming et al., 2011), the need to be prepared for tropical circumstances has been highlighted by the military operations in Somalia, Rwanda, Haiti, Panama, and East Timor.

E. Inadequate Literature Review for PE4

A search of the database for literature reviews reveals an insufficient journal devoted to the subject of "Plastic Explosive PE4". One possible implication of this is the immaturity of knowledge contribution and research inquiry on this subject, as well as the limited advancement of explosive engineering, particularly military explosion engineering. There is a small chance the situation may improve in the long run, as more scholars with this background are interested in supporting national research agencies through these research areas. However, in order to ensure an effective method in obtaining literature review material for this research endeavour is followed, several comprehensive research databases have been chosen accordingly.

Scopus Database discovered a total of 13 documents when the year range is set between 2023 and 2017. The use Keywords are TITLE-ABS-KEY (plastic AND explosive AND Pe4) AND (LIMIT-TO (PUBYEAR, 2022) OR LIMIT-TO (PUBYEAR, 2021) OR LIMIT-TO (PUBYEAR, 2020) OR LIMIT-TO (PUBYEAR, 2020), 2019) OR LIMIT-TO (PUBYEAR, 2018) OR LIMIT-TO (PUBYEAR, 2017)). This finding implies that a lack of publication may result in insufficient argumentation and immaturity in the field of explosion engineering. Using a Google Scholar Database, with the year's limit set between 2023 and 2017, Google Scholar lists a total of 223 documents. A search keyword is Plastic Explosive PE4. Academics and researchers in the explosion research cluster may be keen to publish journals in the field of explosion engineering through the Google Scholar database.

While using a well-known database for Engineering, IEEExplore listed zero documents during searching. The year's limit is set between 2023 and 2017, and the search keyword is Plastic Explosive PE4. The topic is likely extremely new to the IEEExplore database. However, while using Springer Link, the database lists 6 documents as a result of searching on the topic of Plastic Explosive PE4. The year ranges are set from 2017 to 2023. It is quite possible that the topic was new to the database in the past five years.

IV. CONCLUSION AND FUTURE WORK

The PE4 is an essential explosive and is widely used in the Malaysian Armed Forces training routine. Unfortunately, because Malaysia is located in a tropical region, it does not take into account the PE4 explosion performance. This study has identified PE4 and product standards that have been developed in Europe, apparently a reasonable approach to discovering a contribution of new knowledge in a tropical matter. Novelty to the research project, this study appears to be the first study to investigate the military PE4 explosion performance due to the Malaysian tropical effect. In addition, these findings will be of interest to developing a military explosive performance model using an artificial neural network. In the future, the study should be repeated using C-4 or Composition C-4 which is in a similar family to PE4, and uses an RDX explosive agent. This C-4 is used by the United States Armed Forces. Moreover, future work may expand the exploration of the climate of Sabah and Sarawak.

A. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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REFERENCES

[1] Abdul Rahim, F. N., Yusof, M. A., Mohamad Nor, N., Ismail, A., Yahya, M. A., Munikanan, V., & Hashim, F. R. (2020). Investigation of PE-4 equivalence of spherical emulsion explosive at different point of initiataion. *Journal of Advanced Research in Dynamical and Control Systems*, *12*(7), 1–8. https://doi.org/10.5373/JARDCS/V12SP7/20202075

[2] Agrawal, Jai. Prakash. (2010). *High Energy Materials: Propellants, Explosives and Pyrotechnics*. Wiley-VCH.

[3] Ahmad, U. K., Rajendran, S., & Abu Hassan, S. (2008). Forensic Analysis of Explosive Residues from Hand Swabs. *The Malaysian Journal of Analytical Sciences*, *12*(1), 213–226.

[4] Alexander, B. (2011). *Forensic Investigation of Explosions* (2nd ed., Vol. 2). CRC Press.

[5] Australian Munitions. (2020, February). *High Explosive Products: Energetic materials for operational effectiveness*. http://www.australian-munitions.com.au/wp-content/uploads/2020/02/High-Explosive-Products.pdf

[6] Aye, G. C., Balcilar, M., Dunne, J. P., Gupta, R., & van Eyden, R. (2014). Military expenditure, economic growth and structural instability: a case study of South Africa. *Defence and Peace Economics*, *25*(6), 619–633. https://doi.org/10.1080/10242694.2014.886432

[7] Baer, M. R., Hall, C. A., Gustavsen, R. L., Hooks, D. E., & Sheffield, S. A. (2007). Isentropic loading experiments of a plastic bonded explosive and constituents. *Journal of Applied Physics*, *101*(3). https://doi.org/10.1063/1.2399881

[8] Bogosian, D., Yokota, M., & Rigby, S. (2016, September 19). TNT equivalence of C-4 and PE4: a review of traditional sources and recent data. *In Proceedings of the 24th Military Aspects of Blast and Shock. MABS*. https://www.researchgate.net/publication/308339134

[9] Campbell, A., & Chapman, M. (2008). *Handbook of Poisoning in dogs and cats* (A. CAMPBELL & M. CHAPMAN, Eds.; pp. 222–225).

[10] Chick, M., & Learmonth, L. (1985). *Determination of Shock Initiation and Detonation Characteristics of PE4 in Proof Test Geometries. Approved for Public Release* (pp. 1–20). Materials Research Laboratories MRL-R-979 .

[11] Choi, C., Callaghan, M., Van Der Schaaf, P., Li, H., & Dixon, B. (2014). *Modification of the Gurney Equation for Explosive Bonding by Slanted Elevation Angle Defence Science and Technology Organisation Approved for Public Release*.

[12] Cooper, P. W. (1977). *Explosives Engineering*. Wiley-VCH.

[13] Davis, W. C. (1998). Introduction to Explosives. In Z. Jonas A. & W. William P. (Eds.), *Explosive Effects and Applications* (pp. 1–22). Springer.

[14] Elbeih, A., Elshenawy, T., Amin, H., Hussein, A. K., & Hammad, S. M. (2019). Preparation and Characterization of a New High-Performance Plastic Explosive in Comparison with Traditional Types. *International Journal of Chemical Engineering*, *2019*, 1–6. https://doi.org/10.1155/2019/4017068

[15] Elbeih, A., Zeman, S., Pachman, J., Elbeih, A., Zeman, S., & Pachman, J. (2013). Effect of Polar Plasticizers on the Characteristics of Selected Cyclic Nitramines Central. *European Journal of Energetic Materials*, *10*(3), 339–349.

[16] Ferreira, F. J. O., Crispim, V. R., & Silva, A. X. (2010). Detection of drugs and explosives using neutron computerized tomography and artificial intelligence techniques. *Applied Radiation and Isotopes*, *68*(6), 1012–1017. https://doi.org/10.1016/j.apradiso.2010.01.019

[17] Fleming, S., Madden, M., Leigh, D., Jackson, P., Menhart, D., & Peralta, R. (2011). *Technical Analysis and Characterization of Southern Cayo, Belize for Tropical Testing and Evaluation of Foliage Penetration Remote Sensing Systems*.

[18] Fleming, S., McDonald, E. V., & Bacon, S. N. (2016). Military Test Site Characterization and Training Future Officers—An Integrated Terrain Analysis Approach. In *Advances in Military Geosciences* (pp. 273–295). Springer. https://doi.org/10.1007/978-1-4939-3429-4_18

[19] Glass, D. (2018). *Explosives for Explosives*. https://www.dvidshub.net/image/4257763/explosives-explosives

[20] Goodpaster, J. V. (2019). Forensic Sciences | Explosives. In *Encyclopedia of Analytical Science* (pp. 23–27). Elsevier. https://doi.org/10.1016/B978-0-12-409547-2.14458-0

[21] Hirnissa, M. T., & Baharom, A. H. (2009). Military Expenditure and Economic Growth in Asean-5 Countries. *Journal of Sustainable Development*, *2*(2).

[22] Hoek, B. (2004). Military explosives and health: organic energetic compound syndrome? In *Medicine, conflict, and survival* (Vol. 20, Issue 4, pp. 326–333). https://doi.org/10.1080/1362369042000285955

[23] Huang, W., Yuan, S., & Wu, H. (2012). Study of low detonation velocity explosives used in explosion welding. *Advanced Materials Research*, *393–395*, 1431–1437. https://doi.org/10.4028/www.scientific.net/AMR.393-395.1431

[24] Langdon, G. S., Kriek, S., & Nurick, G. N. (2020). Influence of venting on the response of scaled aircraft luggage containers subjected to internal blast loading. *International Journal of Impact Engineering*, *141*(103567). https://doi.org/10.1016/j.ijimpeng.2020.103567

[25] Lee, P. R. (1998). Theories and Techniques of Initiation. In Z. Jonas A. & W. William P. (Eds.), *Explosive Effects and Applications* (pp. 173–219). Springer.

[26] Licht, H.-H. (2000). Performance and Sensitivity of Explosives. *Propellants, Explosives, Pyrotechnics.* , *25*(3), 126–132.

[27] Mathieu, J., & Stucki, H. (2004). Military high explosives. *Chimia*, *58*(6), 383–389. https://doi.org/10.2533/000942904777677669

[28] Meyer, R., Köhler, J., & Homburg, A. (2016). *Explosives* (6th ed., Vol. 5). Wiley. https://doi.org/10.1002/3527600515

[29] Ministry of Defence (MoD) U.K. (2006). Use of Demolition, Disposal and EOD Training Ranges. In *Handbook of Defence Land Ranges Safety* (Vol. 4, p. 25). https://www.gov.uk/government/publications/defence-land-ranges-

[30] Mondial Defence Systems Ltd. (2014). *Plastic Explosive No.4 (PE4)*. https://web.archive.org/web/20140319013833/http://www.mondial-defence.com/images/PDF_Data_Sheets/Plastic%20Explosive%20PE4.pdf

[31] Perry, W. L., Sewell, T. D., Glover, B. B., & Dattelbaum, D. M. (2008). Electromagnetically induced localized ignition in secondary high explosives. *Journal of Applied Physics*, *104*(9). https://doi.org/10.1063/1.3002421

[32] Pichtel, J. (2011). *Terrorism and WMDs Awareness and Response: Vol. First Edition*. CRC Press.

[33] Pisharath, S., Ong, Y. J., & Hng, H. H. (2022). Nanoenergetic Composites with Fluoropolymers: Transition from Powders to Structures. *Molecules*, *27*(19), 6598. https://doi.org/10.3390/molecules27196598

[34] Primetake Ltd. (2012). *Primetake Charge Demolition PE 8oz (250g) - PT3520* (Vol. 2). https://primetake.com/wp-content/uploads/sites/5/2016/03/3520.pdf

[35] Provatas, A. (2000). Energetic Polymers and Plasticisers for Explosive Formulations - A Review of Recent Advances. In *Melbourne: DSTO Aeronautical and Maritime Research Laboratory*. DSTO Aeronautical and Maritime Research Laboratory.

[36] Razak, N. S. A., & Alias, A. (2021). The Response of Steel Plates Subjected to Close-in Blast Loads. *IOP Conference Series: Earth and Environmental Science*, *682*(1), 012036. https://doi.org/10.1088/1755-1315/682/1/012036

[37] Rigby, S. E., & Sielicki, P. W. (2015). An Investigation of TNT Equivalence of Hemispherical PE4 Charges. *Engineering Transactions*, *62*(4), 423–435.

[38] Rigby, S., Knighton, R., Clarke, S., & Tyas, A. (2020). Reflected Near-field Blast Pressure Measurements Using High Speed Video. *Experimental Mechanics*, *60*(7), 875–888. https://doi.org/10.1007/s11340-020-00615-3

[39] Sadat Nasiri, S. M., Sadegh-Yazdi, M., Mousavi, S. M., Ziya-Shamami, M., & Mostofi, T. M. (2022). Repeated underwater explosive forming: Experimental investigation and numerical modeling based on coupled Eulerian–Lagrangian approach. *Thin-Walled Structures*, *172*(108860). https://doi.org/10.1016/j.tws.2021.108860

[40] Sharma, P. K., Patel, B. P., & Lal, H. (2017). On the Response of Hemispherical Shell under Blast Loading. *Procedia Engineering, 173*, 533–538. https://doi.org/10.1016/j.proeng.2016.12.085

[41] Sheela A. (2020). Drone As Bomb Detectors. *Elementary Education Online*, *19*(2), 1735–1751. https://doi.org/10.17051/ilkonline.2020.02.696756

[42] Thales. (2010, October 6). *High Explosive Products: Energetic materials for operational effectiveness.* http://www.thalesgroup.com/assets/0/95/389/392/e93b97ee-e77e-43fa-8f7c-07d4061bc14d.pdf?LangType=2057

[43] Thurman, J. T. (2017). *Practical Bomb Scene Investigation: Vol. Third Edition* (Third Edition).

[44] Tyas, A. (2019). Blast Loading From High Explosive Detonation: What We Know and Don't Know. *13th International Conference on Shock and Impact Loads on Structures, SILOS 2019*, 65–76.

[45] Wan Farisan, W. S., Zulkefly, A. K., Norlin, K., & Riayati, A. (2017). Military spending, economic growth and structural instability: Case study for Malaysia. *Defence S and T Technical Bulletin, 10*(1), 88–100.

[46] Zapata, F., & García-Ruiz, C. (2021). Chemical Classification of Explosives. In *Critical Reviews in Analytical Chemistry* (Vol. 51, Issue 7, pp. 656–673). Taylor and Francis Ltd. https://doi.org/10.1080/10408347.2020.1760783

[47] Zeman, S., & Jungová, M. (2016). Sensitivity and Performance of Energetic Materials. *Propellants, Explosives, Pyrotechnics, 41*(3), 426–451. https://doi.org/10.1002/prep.201500351

[48] Zlobin, B., Sil'vestrov, V., Shtertser, A., Plastinin, A., & Kiselev, V. (2014). Enhancement of explosive welding possibilities by the use of emulsion explosive. *Archives of Metallurgy and Materials, 59*(4), 1587–1592. https://doi.org/10.2478/amm-2014-0269