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IMPACT ANALYSIS OF HIGH-SPEED PROJECTILES ON GRANULAR MATERIAL

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Abstract: To enhance ballistic protection, this paper explores the benefits of granular materials compared to traditional materials used in this field. Currently, ballistic protection employs various materials either individually or in combination, such as armored steels, ceramic layers, composite materials, and granular structures. This study investigates the interaction of projectiles with each type of material, as well as the effects of combining different material layers. Granular materials consist of macroscopic particles, each with its own degrees of freedom. Collisions between these particles transfer energy from the solid body to individual particles, leading to energy dissipation that can halt the motion of particles within the granular material. The primary objective of this research is to analyze the results of projectile impacts on various material obstacles using a mathematical model for image processing.

Keywords: Granular materials, ballistic protection, optical methods, energy dissipation, obstacle, projectile.

1. INTRUDUCTION

This research adopts a multidisciplinary approach to applying optical methods for investigating the dynamic processes involved in projectile interactions with various obstacles. The aim is to utilize optical techniques, such as high-speed and thermal imaging, to study how projectiles interact with obstacles composed of different materials [1].

The methodology aims to uncover how the structure of obstacles made from diverse materials affects energy transformation and material displacement during high-speed projectile collisions. This understanding is intended to inform the design and use of specific materials and structures for ballistic protection. Armored steel, renowned for its ability to absorb kinetic energy and halt projectiles, is highlighted for its mechanical properties and ballistic resistance [1,2,3].

Conversely, ceramic materials, while superior to metals for protective applications, must be combined with ballistic fiber composites. These ceramic composites, valued for their high strength, low weight, and excellent temperature resistance, are predominantly used in aviation and other military applications.

The authors propose to explore the behavior of projectile impacts with obstacles made of granular materials, offering new insights into potential advancements in ballistic protection technologies [4,5,6] .

2. MATERIAL AND METHODS

The developed optical methods enable the analysis of research results without interfering with the physical processes involved [7,8,9]. This research aims to demonstrate the application of image processing methods and the findings obtained by these techniques. The authors provide a comparative explanation of how these methods are used in optics to detect and determine the influencing parameters during the interaction of projectiles with obstacles of different characteristics.

In addition, with this study, the authors present a simple image processing procedure that helps engineers to easily select appropriate materials for different applications.

2.1. Granular matters

Granular materials consist of macroscopic particles ranging from approximately 1 μm and larger, with no practical upper size limit. These particles collectively exhibit solid-like behavior while each individual particle retains its own degrees of freedom.

Figure. 1. *Granular material*

In the event of a collision between these particles, energy is transferred from the solid body (projectile) to the individual particles. In this case, energy dissipation occurs, which can lead to the cessation of movement of macroscopic particles within the granular material. Granular materials have significant military applications [10,11,12].

This paper investigates the behavior of granular materials with and without binders. These advanced materials possess properties that allow them to respond to external stimuli and were primarily developed for military and aerospace applications before transitioning to civilian use.

2.2. Methods

Numerous optical methods have been developed and used in mechanical engineering to investigate the interaction between projectiles and various granular materials used as obstacles. These methods, although advanced and effective, often require expensive equipment, significant time to conduct experiments, and significant resources to process the results. In the case of using the methods presented by the authors in this paper, it is possible to perform an analysis of the effect of a solid body on granular materials or any other materials in a simple way and to select the best or most optimal material for further use in a simple way. [13,14,15].

These optical methods provide modern and practical techniques for determining relevant research outcomes allowing detailed analysis. The aim of this research is to demonstrate the advantages of using granular materials as barriers, emphasizing their economy, simplicity in material selection and ease of application in experiments. The study specifically focuses on the processing of images captured by high-speed and thermal cameras to illustrate the benefits of granular materials in ballistic protection [16,17] .

2.2. Results

Experimental recordings were conducted using a high-speed and thermal imaging camera. The recorded frames of the target were analyzed, which consisted of two plates. The first target was an existing protective layer used for defensive purposes,

Table 1. *Data on plates made of granular materials*

Plates	Dimensions [mm]	Dimensions layers [mm]	Layer volume [mm^3]	Volume of binding material [mm^3]
1	267x290x21	267x290x7	542010	2,7x10^5 water
2				2,1x10^5 water, 4,7x10^5 construction cement

and the second target was composed of three layers of granular material with different granulations, incorporating construction cement as a binding matrix. Data regarding the panels made of granular materials are presented in Table 1.

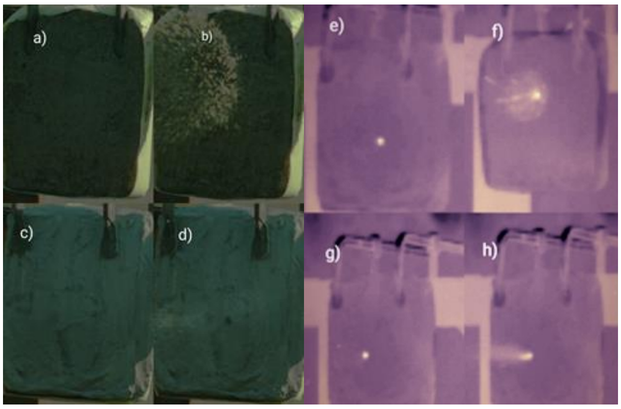

Figure 2. *Target shooting a) immediately before shooting the first target b) after shooting the first target c) immediately before shooting the second target d) after shooting the second target e) temperature profile before shooting the first target f) temperature profile after shooting the first target g) temperature profile before shooting at another target h) temperature profile after shooting at another target*

Based on the acquired recordings, it was observed that the dissipation of kinetic energy (Ek) is higher in targets made of granular materials without binding material compared to those with a binding material such as construction cement. Additionally the temperature recorded when the projectile impact the first target is lower than when it impacts the second target.

Figure 2 shows shots fired at the targets. In Figure 2, (a) displays the target hatch immediately before and after the shot, while (b) provides a comparison. When comparing the impact on target number 2, (c) and (d), with the first target, it is evident that greater energy dissipation occurs in the first target, suggesting that target 1 (granular matter) may be better suited for protective equipment due to its superior energy dissipation characteristics. Analyzing the temperature profile in Figure 2, (e) and (g) show similar openings when the projectile enters the first and second targets, but differing temperature profiles. The second target (granular material with construction cement) exhibits higher temperatures concentrated over a smaller surface area. These observations indicate that the first target (granular material without binders) possesses superior characteristics for use as protective equipment.

When the projectile hits different types of obstacles, the target heats up. Depending on the type of target, different maximum temperatures occur, as shown in the following diagrams. The temperature that appears when the projectile hits an obstacle is read from the thermogram. Data on temperature distribution are provided in diagrams 1, 2, and 3:

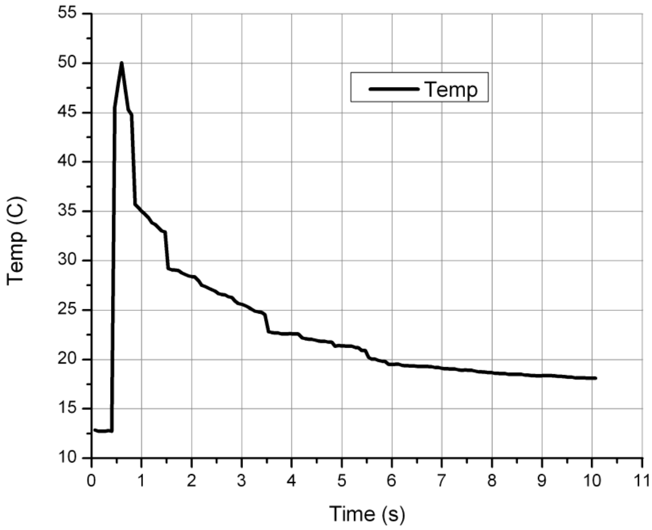

Diagram 1. *Temperature distribution at the moment of impact of the projectile into the protective plate*

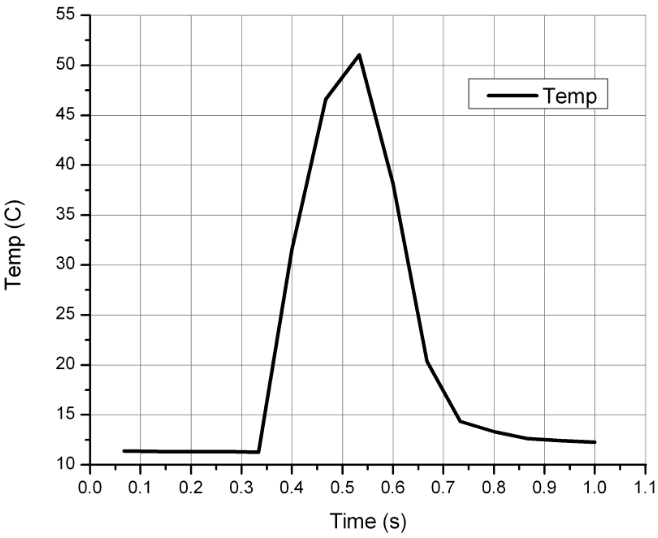

Diagram 2*. Temperature distribution diagram at the moment the projectile hits the sand*

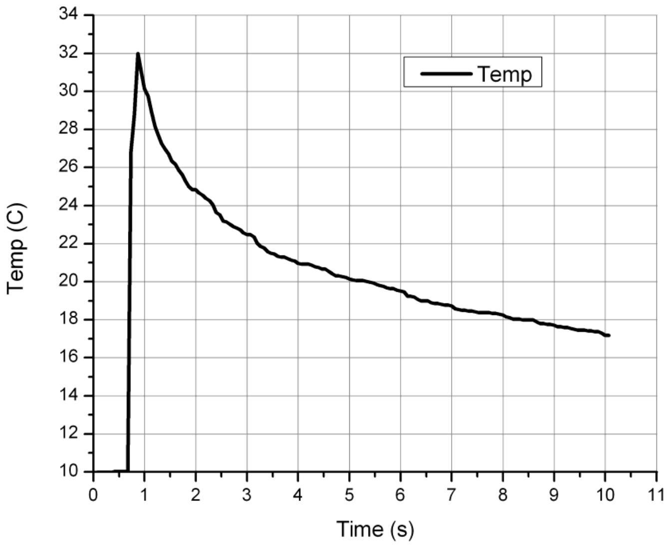

Diagram 3. *Temperature distribution at the moment of impact of the projectile into the concrete*

4. DISCUSION

Comparing the temperature distribution diagrams at the moment the projectile hits the target reveals that the highest temperatures occur in granular materials, leading to greater dissipation of the projectile's energy. Additionally, the temperature rise in granular materials is more rapid, resulting in faster energy dissipation. Based on these observations, it can be concluded that granular materials are highly effective in absorbing and transmitting the energy of impacting substances. Therefore, their application in protective equipment is particularly advantageous.

5. CONCULSION

This research addresses the need for more reliable models to determine the dynamic interaction parameters of projectiles with various materials, leveraging advancements in modern optical and computer technologies. Current methods depend on semi-empirical models and numerical calculations with predefined dynamic material characteristics. By defining modern methodologies for examining these parameters, this research facilitates the identification of key factors in the development, optimization, and construction of advanced ballistic protection systems. It also provides a simpler approach to selecting materials for military and other purposes.

From the temperature distribution diagrams at the moment of projectile impact, it is evident that granular materials achieve the highest temperatures, leading to greater energy dissipation. The rapid temperature increase in granular materials results in faster energy dissipation. Consequently, granular materials are highly effective in absorbing and transmitting energy from impacting substances, making them particularly suitable for protective applications.

Additionally, granular materials cool down faster than traditional protective plates and concrete, which is advantageous for protecting soldiers in battle. Based on these findings, it is clear that granular materials will likely be widely used in the production of protective components for military equipment.

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Table 2. *Target heating and cooling data*

Material	Protective plate	Sand (Granular matters)	Concrete
Maximum temperature [°C]	51	52	32
Warm-up time [s]	0,45	0,34	0,7
Cooling time [s]	1	0,7	1,2

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АНАЛИЗА УТИЦАЈА ПРОЈЕКТИЛА ВЕЛИКЕ БРЗИНЕ НА ГРАНУЛИРАНОМ МАТЕРИЈАЛУ

Сажетак: Да би се побољшала балистичка заштита, овај рад истражује предности зрнастих материјала у поређењу са традиционалним материјалима који се користе у овој области. Тренутно, балистичка заштита користи различите материјале, појединачно или у комбинацији, као што су оклопни челици, керамички слојеви, композитни материјали и грануларне структуре. Ова студија истражује интеракцију пројектила са сваком врстом материјала, као и ефекте комбиновања различитих слојева материјала. Зрнасти материјали се састоје од макроскопских честица, свака са својим степеном слободе. Судари између ових честица преносе енергију са чврстог тела на појединачне честице, што доводи до дисипације енергије која може зауставити кретање честица унутар грануларног материјала. Примарни циљ овог истраживања је анализа резултата удара пројектила на различите материјалне препреке коришћењем математичког модела за обраду слике.

Кључне речи: грануларни материјали, балистичка заштита, оптичке методе, дисипација енергије, препрека, пројектил.

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