

# Comparison of Impact Absorption Properties Between Colloidal and Non-Colloidal Materials

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## ABSTRACT

Impact absorbing materials are used in many different, industrially relevant areas, from sports to military and defense. This review aims to address the impact absorption of two categories of materials: colloidal and non-colloidal materials. Some model systems are considered: first is Oobleck (corn starch and water), a well-known colloidal system that absorbs shock through shear-induced jamming via frictional particle contacts. Second is dry cornmeal, a granular system which absorbs impact energy through compression and friction under adequate confinement conditions. Lastly, a polymeric system comprising polyborosiloxane (PBS), which absorbs impact through rate-dependent viscoelastic stiffening governed by the Deborah number and temperature-dependent bond dynamics. This review compares the shock absorbing mechanisms and performance of each of these chemically unique systems and aims to provide criteria for selecting the suitable material for a specific application. In addition to mapping mechanisms, practical selection rules are outlined, including when to prefer reversible stiffening (colloids and polymers) versus irreversible compaction (granular solids), how thickness requirements and mass penalties scale with protection level, and what environmental limits (temperature, humidity) matter in field applications.

**Keywords:** Impact absorption; Colloids; Granular Materials; Polyborosiloxane; Shear Thickening; Rheology; Non-Newtonian Fluids

## INTRODUCTION

Impact absorption refers to the transfer reduction of kinetic energy by making the duration of impact longer, or distributing the force over a larger area. This impact absorption technique is used in various areas, from sports, to safety and defense (1). Without efficient and

effective absorbing techniques, the concentrated force can lead to detrimental structural failure, damage, or injury. Impact absorption is therefore a key area for innovation. To move from concept to practice, the following sections link basic physics to material classes and then to design choices for real equipment.

At its core, effective impact mitigation either lengthens the stopping time (impulse spreading), increases the engaged mass/area (load distribution), or triggers a rate-dependent stiffening transition that resists rapid deformation (2). In sports, pads and helmets that stay soft while you move but go stiff on a hit (1, 3). In vehicles, crushable zones that collapse in a controlled way, and in

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defense, flexible armor that can stop fragments *yet allow* mobility (4).

One of the traditional impact absorbing materials are polymeric foams or hard shells (1). These materials are commonly used in car bumpers, helmets, and body armor. However, these materials have limitations: energy absorption often relies on controlled crushing regions which limits multi-hit durability, and high rigidity or thickness which reduces comfort and mobility and increases the cost (1, 5, 6). These drawbacks motivate new approaches and materials that have higher comfort levels without losing impact absorption.

A phenomenon called shear-thickening aids in solving these drawbacks of traditional impact absorbing materials. Shear-thickening is exhibited when a material's viscosity and stiffness dramatically increase under a high shear rate (7, 8). Shear rate is the rate at which adjacent layers of a fluid, or layers within a solid material, move relative to each other. Shear-thickening behavior can happen as a result of both physical and chemical interactions (9). Physical interactions comprise collisions and frictional jamming of particles and the entanglement of the long polymer chains in the fluid which serve to resist flow and increase viscosity (7, 10). Chemical interactions involve the formation and breakage of temporary bonds, such as hydrogen bonds or ionic interactions, which affect the material's response to stress (11). Both of these interactions contribute to the overall shear-thickening effect and are crucial for understanding and optimizing the performance of impact absorbing materials.

## THE RHEOLOGY OF IMPACT ABSORPTION

Rheology is the study of how materials flow and deform under applied forces. It provides a framework for understanding the relationship between stress (force per unit area), strain (deformation), and strain rate (speed of deformation). This relationship is central to analyzing how materials respond to impacts. Unlike simple elastic solids, which obey Hooke's law, or Newtonian fluids, which exhibit constant viscosity, many impact-absorbing materials display non-Newtonian behavior—their viscosity changes with the rate of applied stress (12). This rate-dependent response is key to effective energy dissipation during rapid impacts.

A material's rheological behavior is characterized by its constitutive equation, which relates stress to strain and strain rate. For viscoelastic materials, both elastic and viscous components contribute to the response, often

described by models such as the Maxwell or Kelvin-Voigt models (12). In the context of impact absorption, the relevant parameter is often the dimensionless Deborah number ( $De$ ), defined as the ratio of the material's relaxation time to the observation time (13). When  $De$  is high (rapid impact), the material behaves more like an elastic solid; when  $De$  is low (slow deformation), it behaves more like a viscous fluid. This transition underlies the protective function of many rate-sensitive materials.

### Shear-Thickening

Shear-thickening, also known as dilatancy, is a non-Newtonian behavior where a material's viscosity increases with increasing shear rate (7, 9). This phenomenon is particularly useful for impact absorption because it allows a material to remain flexible under normal conditions but stiffen dramatically upon sudden impact. The underlying mechanism depends on the material type. In colloidal suspensions, shear-thickening arises from the transition of particles from a lubricated, flowing state to a frictional, jammed state under rapid shear (14, 15). This jamming transition is reversible: once the stress is removed, the particles can flow again. In contrast, polymeric systems may exhibit shear-thickening due to strain-induced alignment or entanglement of polymer chains, which temporarily resist flow (16). The degree and onset of shear-thickening are influenced by several factors, including particle concentration, particle shape, surface chemistry, and the presence of stabilizing agents (17). For example, higher particle volume fractions generally lead to more pronounced shear-thickening at lower shear rates. Understanding these factors is critical for tailoring materials to specific protective applications, such as body armor or sports padding, where controlled stiffening under impact is desired.

### Shear-Thinning

Shear-thinning is the opposite behavior, where viscosity decreases with an increasing shear rate (12). While shear-thinning is less commonly exploited for impact absorption, it plays an important role in processing and application of protective materials. For instance, shear-thinning allows suspensions to be easily pumped or coated onto fabrics at low viscosity, yet remain stable and viscous at rest. Some materials exhibit both shear-thinning at low shear rates and shear-thickening at high shear rates, providing a versatile response profile (18). This dual behavior can be advantageous in applications requiring both ease of handling and impact protection.

## COLLOIDAL MATERIALS

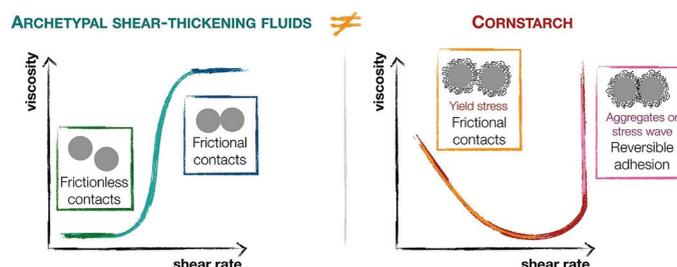
Colloidal materials consist of microscopic particles (typically 1 nm to 10  $\mu\text{m}$  in diameter) dispersed in a continuous medium, such as a liquid. These materials exhibit unique rheological properties due to the interactions between particles, which can include hydrodynamic forces, electrostatic repulsion, van der Waals attraction, and frictional contact (10). Unlike colloidal suspensions that exhibit reversible shear-thickening behavior through particle jamming, granular media (discussed later) depend on irreversible compaction and energy loss through friction. The most widely studied colloidal impact-absorbing material is a suspension of cornstarch in water, commonly known as Oobleck.

Oobleck is a dense suspension of cornstarch particles in water, typically at a volume fraction of 40-50% (19). Visual characterization reveals that while the suspension maintains a fluid state at equilibrium, it undergoes a phase-like transition under stress, exhibiting solid-like properties distinct from its resting state (Figure 1) (19). It is a classic example of a shear-thickening fluid (STF). Under slow or gentle stirring, Oobleck flows like a liquid. However, when subjected to rapid impact or high shear rates, it behaves like a solid, resisting deformation and absorbing energy (18, 19). This dramatic transition is due to the jamming of cornstarch particles under stress, where frictional contacts between particles create a transient solid-like network (15).



**Figure 1.** A shear-thickening fluid (Oobleck) made from cornstarch and water, demonstrating its solid-like properties under pressure. Image credit: The Best Ideas for Kids (19).

The mechanism of shear-thickening in Oobleck has been extensively studied. At low shear rates, the particles are suspended in a lubricated state, with thin layers of water separating them. As the shear rate increases, hydrodynamic forces push particles together, overcoming the repulsive forces and causing direct frictional contact (14, 15). This transition from a lubricated to a frictional state leads to a rapid increase in viscosity and the formation of force chains—linear arrangements of particles that transmit stress through the material (20). A key theoretical distinction is illustrated by the contrast between standard frictional contact models and the abrupt viscosity discontinuity inherent to the jamming transition in cornstarch suspensions (Figure 2) (11). These force chains are responsible for the solid-like resistance observed during impact. Once the stress is removed, the force chains disintegrate, and the material returns to its liquid-like state, demonstrating the reversibility of the shear-thickening mechanism.



**Figure 2.** A comparison of shear-thickening models, contrasting the standard frictional contact model (left) with the proposed adhesive model for cornstarch (right) (11).

Oobleck has been explored for various protective applications, including liquid body armor, sports padding, and vibration damping (1, 3). Its advantages include low cost, ease of preparation, and the ability to conform to complex shapes. However, it also has limitations, such as sensitivity to temperature (viscosity decreases at higher temperatures), evaporation of water over time, and potential for particle settling or phase separation (11). These factors must be considered when designing practical applications. A summary of these characteristics is provided in Table 1.

Granular materials are collections of discrete solid particles, such as sand, gravel, or dry cornmeal, that interact primarily through contact forces (friction and collision) rather than through a continuous medium (20). Unlike fluid-based systems, energy dissipation in

**Table 1.** Advantages and Disadvantages of Colloidal Materials

| Advantages                                           | Disadvantages                                   |
|------------------------------------------------------|-------------------------------------------------|
| Reversible stiffening allows multi-hit protection    | Sensitivity to temperature and humidity         |
| Conforms to complex shapes and surfaces              | Water evaporation reduces long-term stability   |
| Low cost and easy to prepare (e.g., Oobleck)         | Particle settling or phase separation over time |
| Effective energy dissipation through jamming         | Limited mechanical strength in thin layers      |
| Tunable rheology by adjusting particle concentration | Potential for leakage if not properly contained |

these media is governed fundamentally by the collective mechanical interaction and irreversible compaction of discrete macroscopic grains (Figure 3) (21). Unlike colloidal suspensions, granular materials do not exhibit reversible shear-thickening; instead, they absorb impact energy through irreversible compaction, rearrangement, and frictional dissipation (22). The behavior of granular materials under impact is complex and depends on factors such as particle size distribution, shape, packing density, and confinement conditions (20).



**Figure 3.** Grains of sand, an example of a granular material that dissipates impact energy through friction and compaction. Image credit: Heidelberg Materials (21).

### Dry Cornmeal

Dry cornmeal is a granular material consisting of irregularly shaped particles derived from ground corn kernels. When confined in a container or enclosure, dry cornmeal can absorb impact energy through several mechanisms: particle rearrangement, frictional sliding, and compaction (21). Upon impact, the kinetic energy of the impacting object is transferred to the granular medium, causing particles to move, collide, and compress. This process dissipates energy as heat and sound, reducing the force transmitted to the underlying surface (22).

The effectiveness of dry cornmeal as an impact

absorber depends strongly on confinement. In an open or loosely confined system, particles can easily flow away from the impact site, providing little resistance. However, in a well-confined system, the particles are forced to interact more strongly, forming transient force chains that distribute the impact load over a larger area (20). These force chains are similar to those observed in colloidal systems, but they are formed through direct mechanical contact rather than hydrodynamic or electrostatic interactions. Unlike the reversible jamming in colloids, the compaction in granular materials is largely irreversible: once the particles are compressed, they do not spontaneously return to their original configuration.

Granular materials have been used in various impact absorption applications, including crash barriers, packaging, and erosion control (20). Their advantages include low cost, abundance, and simplicity. However, they also have significant limitations: they require adequate confinement to be effective, they add considerable weight, and they do not provide the same level of multi-hit protection as reversible shear-thickening fluids (22). Additionally, the irregular and heterogeneous nature of granular materials can lead to unpredictable performance, making them less suitable for applications requiring precise control over impact response. The key advantages and disadvantages of granular systems are outlined in Table 2.

### POLYMERIC MATERIALS

Polymeric materials are composed of long-chain molecules (polymers) that can exhibit a wide range of mechanical and rheological properties depending on their molecular structure, cross-linking, and environmental conditions (23). Unlike colloidal and granular materials, polymers can absorb impact energy through viscoelastic mechanisms, where both elastic (energy storage) and viscous (energy dissipation) components contribute to

**Table 2.** Advantages and Disadvantages of Granular Materials

| Advantages                                                   | Disadvantages                                       |
|--------------------------------------------------------------|-----------------------------------------------------|
| Low cost and widely available                                | Requires strong confinement to be effective         |
| Simple to implement and use                                  | Irreversible compaction limits multi-hit capability |
| Effective energy dissipation through friction and compaction | Significant weight and bulk                         |
| No chemical degradation or evaporation                       | Unpredictable performance due to heterogeneity      |
| Environmentally benign and recyclable                        | Limited conformability to complex shapes            |

the overall response (12). The balance between these components is governed by the Deborah number ( $De$ ), which compares the material's relaxation time to the timescale of the applied deformation (13). While colloidal suspensions rely on reversible particle jamming and granular media on irreversible compaction, polymeric materials achieve impact absorption through rate-dependent viscoelastic stiffening and controlled energy dissipation via molecular bond dynamics.

### Polyborosiloxane (PBS)

Polyborosiloxane (PBS), commonly known as “Silly Putty,” is a viscoelastic polymer formed by cross-linking polydimethylsiloxane with boric acid (25). The resulting material exhibits remarkable rate-dependent behavior: it flows like a viscous liquid under slow deformation but behaves like an elastic solid under rapid impact (16). Moreover, the material's adaptability is underscored by its capacity to function as both a viscous liquid for molding and a fracture-resistant solid for protection, contingent upon the applied deformation rate (Figure 4) (24).

This behavior is due to the dynamic nature of the borate cross-links, which can break and reform on a timescale that depends on temperature and deformation rate (24). At low strain rates (high Deborah number), the borate bonds have sufficient time to break and reform, allowing the polymer chains to flow past one another. This gives PBS its characteristic ability to stretch, bounce, and flow. However, at high strain rates (low Deborah number), the bonds do not have time to rearrange, and the material behaves as a cross-linked elastic solid, resisting deformation and absorbing energy (13, 16). This rate-dependent stiffening is analogous to the shear-thickening observed in colloidal systems, but it arises from a fundamentally different mechanism: the kinetics of reversible chemical bonds rather than the jamming of discrete particles.

The viscoelastic properties of PBS can be tuned by

varying the molecular weight of the polymer, the degree of cross-linking, and the temperature (24, 25). Higher cross-link density generally increases the elastic modulus and reduces the relaxation time, making the material stiffer and more responsive to rapid impacts. Temperature also plays a critical role: at higher temperatures, the borate bonds break and reform more rapidly, shifting the material toward more fluid-like behavior (24). Conversely, at lower temperatures, the bonds are more stable, and the material becomes more solid-like.

PBS has been explored for various impact absorption applications, including sports equipment, protective



**Figure 4.** Representation of the use of PBS, including its use as a rheological liquid (a), in protective materials for mechanical impact resistance (b), in fire-resistant ceramics (c), and in self-healing material systems (d) (24).

**Table 3.** Advantages and Disadvantages of Polymeric Materials

| Advantages                                        | Disadvantages                                        |
|---------------------------------------------------|------------------------------------------------------|
| Excellent rate-dependent energy dissipation       | Sensitivity to temperature and humidity              |
| Tunable mechanical properties through chemistry   | Potential for creep and permanent deformation        |
| Conforms well to complex shapes                   | Relatively high material and processing cost         |
| Reversible stiffening allows multi-hit protection | Limited long-term stability under extreme conditions |
| Versatile for various protective applications     | Requires careful formulation and quality control     |

padding, and vibration damping (16). Its advantages include excellent energy dissipation, tunable mechanical properties, and the ability to conform to complex shapes. However, it also has limitations, such as sensitivity to temperature and humidity (which can affect the borate cross-links), potential for creep and permanent deformation under sustained load, and relatively high cost compared to simpler materials like Oobleck or dry cornmeal (24). These trade-offs are further detailed in Table 3.

### COMPARATIVE ANALYSIS AND MATERIAL SELECTION CRITERIA

The three material classes, colloidal, granular, and polymeric, each offer distinct advantages and limitations for impact absorption. The choice of material depends on the specific application requirements, including the nature of the impact (single versus multi-hit, low versus high energy), environmental conditions (temperature, humidity), weight and thickness constraints, and cost considerations. This section provides a comparative framework to guide material selection, building on the rheological principles and mechanisms discussed earlier.

**Mechanism Comparison** Colloidal materials (Oobleck) absorb impact through reversible shear-thickening, driven by the jamming of suspended particles under high shear rates. The transition from a lubricated to a frictional state creates transient force chains that resist deformation and dissipate energy (15). This mechanism is highly rate-dependent and reversible: once the impact stress is removed, the material returns to its fluid-like state. The reversibility makes colloidal systems ideal for multi-hit protection, where the material must repeatedly absorb impacts without permanent degradation.

Granular materials (dry cornmeal) absorb impact through irreversible compaction and frictional energy dissipation. Upon impact, particles rearrange, collide, and compress, forming force chains that distribute the

load (20). However, unlike colloids, the compaction is not reversible: the particles remain in their compressed state after the impact. This limits the multi-hit capability of granular materials, as subsequent impacts encounter a pre-compressed medium with reduced energy absorption capacity. Additionally, granular materials require strong confinement to prevent particle flow and maintain effective force chain networks.

Polymeric materials (PBS) absorb impact through rate-dependent viscoelastic stiffening, governed by the dynamics of reversible chemical cross-links. At high strain rates, the cross-links do not have time to break and reform, causing the material to behave as an elastic solid that resists deformation and stores energy (13, 16). At low strain rates, the cross-links can rearrange, allowing the material to flow and dissipate energy viscously. This dual behavior provides both energy storage and dissipation, making polymeric materials versatile for a wide range of impact scenarios. Like colloids, the stiffening is reversible, enabling multi-hit protection.

**Performance Metrics** Energy absorption capacity is a critical metric for impact protection. Colloidal and polymeric materials generally provide higher energy absorption per unit mass than granular materials, due to their more efficient stress distribution and reversible mechanisms (1, 2). However, granular materials can absorb large amounts of energy in bulk applications, such as crash barriers, where weight is less of a concern (20).

Multi-hit durability is another important consideration. Colloidal and polymeric materials excel in this regard, as their reversible mechanisms allow them to recover after each impact (1, 2). In contrast, granular materials suffer from irreversible compaction, which reduces their effectiveness in repeated impacts unless the material is replaced or re-fluffed (22).

Thickness and weight requirements vary significantly. Colloidal and polymeric materials can provide effective protection in relatively thin layers (a few millimeters to centimeters), making them suitable for wearable

applications such as body armor and sports padding (1,3). Granular materials, on the other hand, typically require thicker layers and add considerable weight, limiting their use in weight-sensitive applications (22).

#### Environmental and Practical Considerations

Colloidal systems (Oobleck) are sensitive to temperature changes, with viscosity decreasing at higher temperatures and the risk of freezing at low temperatures (11). Polymeric materials (PBS) also exhibit temperature-dependent behavior, with the viscoelastic properties shifting as temperature changes the kinetics of bond dynamics (24). Granular materials are generally less sensitive to temperature, making them more robust in extreme environments (20).

Humidity and moisture can affect colloidal systems, as water evaporation or absorption can alter the particle concentration and rheological properties (11). Polymeric materials may also be affected by moisture, particularly if the cross-linking chemistry is sensitive to hydrolysis (24). Granular materials are largely unaffected by humidity, provided they are kept dry and free-flowing.

Cost and availability are practical considerations. Granular materials (such as sand or cornmeal) are the least expensive and most widely available, making them attractive for large-scale or disposable applications

(20). Colloidal systems (Oobleck) are also relatively inexpensive and easy to prepare, though they require containment and maintenance (1). Polymeric materials (PBS) are generally the most expensive, due to the cost of raw materials and processing, but they offer superior performance and tunability (24).

A rigorous property-based comparison of these factors is presented in Table 4.

#### Selection Guidelines

Based on the comparative analysis, the choice of impact-absorbing material depends on the specific performance requirements of the application. For multi-hit, wearable protection, such as body armor or sports padding, colloidal and polymeric materials are generally the most effective. Colloidal systems like Oobleck provide cost-effective, reversible stiffening, although they require proper containment and can be sensitive to temperature and humidity. Polymeric materials such as PBS offer greater tunability and higher mechanical performance, but at a substantially higher cost.

For applications involving single-hit, high-energy absorption, including crash barriers and protective packaging, granular materials are more suitable. When properly confined, these materials are inexpensive and

**Table 4.** Rigorous Property-Based Comparison

| Parameter              | Colloidal STS (Oobleck)                                                                                                            | Granular Solids (Cornmeal)                                    | Polymeric STG (PBS)                                                            |
|------------------------|------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------|--------------------------------------------------------------------------------|
| Primary Mechanism      | Hydrodynamic drag and frictional jamming                                                                                           | Frictional sliding, inelastic collisions, plastic deformation | Viscoelastic dissipation, chain entanglement                                   |
| Reversibility          | Fully Reversible - recovers to fluid state                                                                                         | Largely Irreversible - persistent compacted state             | Fully Reversible - recovers to gel state                                       |
| Activation Condition   | Critical shear rate ( $\dot{\gamma}_c = 10^2\text{-}10^3 \text{ s}^{-1}$ ) or shear stress ( $\tau_c = 10\text{-}100 \text{ Pa}$ ) | Compressive stress under strong confinement                   | Critical deformation rate where $De = \lambda/t \gg 1$                         |
| Thickness Requirements | 5-15 mm optimal; minimum 3-5 mm                                                                                                    | 20-50 mm; must be $>15$ grain diameters                       | 3-12 mm; rate and temperature dependent                                        |
| Weight Penalty         | 0.5-2.0 kg/m <sup>2</sup>                                                                                                          | 30-125 kg/m <sup>2</sup>                                      | 3-12 kg/m <sup>2</sup>                                                         |
| Confinement Needs      | Low - encapsulation prevents leakage                                                                                               | High - essential for jamming mechanism                        | Low - incorporation prevents creep                                             |
| Temperature Range      | Narrow - limited by carrier fluid properties (0-60°C)                                                                              | Very wide - limited by grain properties (-50 to +200°C)       | Specific window - defined by relaxation time ( $\pm 20^\circ\text{C}$ optimal) |
| Multi-Hit Capability   | Excellent (reversible mechanism)                                                                                                   | Poor/None (irreversible compaction)                           | Excellent (non-destructive mechanism)                                          |
| Cost & Complexity      | Very low - simple ingredients (\$0.10-1.00/kg)                                                                                     | Very low - readily available (\$0.05-0.50/kg)                 | High - controlled synthesis required (\$10-100/kg)                             |

capable of absorbing large amounts of energy, though their effectiveness is limited by their high weight and irreversible compaction after impact.

Environmental conditions also play an important role in determining material suitability. Granular materials are the most robust option for extreme temperature environments, whereas colloidal and polymeric systems may require encapsulation or environmental conditioning to maintain their protective behavior. In situations where minimizing weight is critical—such as aerospace structures or portable protective equipment—colloidal or polymeric materials are preferred because they provide effective impact mitigation in thin, lightweight layers.

Cost considerations further inform material selection. For low-cost or large-scale applications, granular or colloidal materials offer the most economical solutions. Polymeric materials, given their higher cost of synthesis and processing, are best reserved for applications where their enhanced tunability and superior performance justify the additional expense.

## CONCLUSION

This review has compared the impact absorption properties of three distinct material classes: colloidal, granular, and polymeric. Each class offers unique mechanisms and performance characteristics that make them suitable for different applications. Colloidal materials, exemplified by Oobleck, provide reversible shear-thickening through particle jamming, making them ideal for multi-hit, wearable protection. Granular materials, such as dry cornmeal, absorb energy through irreversible compaction and friction, suitable for bulk, single-hit applications. Polymeric materials, represented by polyborosiloxane (PBS), exhibit rate-dependent viscoelastic stiffening governed by dynamic cross-links, offering tunable and versatile impact protection.

The selection of an appropriate impact-absorbing material requires careful consideration of the application requirements, including the nature of the impact, environmental conditions, weight and thickness of constraints, and cost. By understanding the underlying rheological mechanisms and performance of trade-offs, engineers and designers can make informed decisions to optimize protection while balancing practical considerations. Future research should focus on developing hybrid materials that combine the best features of each class, as well as on improving the environmental stability and scalability of advanced impact-absorbing systems.

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## CONFLICT OF INTEREST

The author declares that there are no conflicts of interest related to this work.

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