International Journal of Scientific Research & Engineering Trends
Volume 10, Issue 6, Nov-Dec-2024, ISSN (Online): 2395-566X

Development of Lightweight High-Entropy Nanocomposite Materials for Enhanced Protective Hat

Abdulaziz S. Alaboodi, S. Sivasankaran, R. Karunanithi, Khalid Algadah
Department of Mechanical Engineering, College of Engineering
Burydah, Qassim University, Saudi Arabia

Abstract- The research project focuses on the design and development of lightweight, high-entropy nanocomposite materials for hard hats and helmets, aimed at enhancing safety across various industrial sectors, including construction and manufacturing. By blending five thermoplastic polymers—high-density polyethylene (HDPE), polycarbonate (PC), polypropylene (PPE), polyethylene terephthalate (PET), and polybutylene terephthalate (PBT) with glass fibers and nanographene, the study produced novel composite materials. Mechanical testing demonstrated improved strength and impact resistance, with a notable 13% weight reduction in the final prototype compared to traditional materials. The project utilized advanced characterization techniques, including FTIR and XRD, to validate the material properties. These innovative materials not only meet industry safety standards but also align with environmental considerations by utilizing readily available raw materials.

Index Terms- High-Entropy Nanocomposites, Lightweight Materials, Hard Hats, Mechanical Testing, Thermoplastic Polymers, Industrial Safety

I. INTRODUCTION

The need for lightweight and durable protective headgear has become increasingly critical across various industrial sectors, including construction, manufacturing, and aerospace. Hard hats and helmets are essential for safeguarding against head injuries from falling objects and impacts. Several studies have explored the mechanical performance of helmets made from composite materials [1-17]. One study investigated bio-composite helmets using natural fibers and found that while these materials were lightweight, they did not perform as well in impact tests compared to synthetic composites [18]. Similarly, glass/jute/epoxy composite helmets demonstrated decent impact resistance but were heavier than desired [19]. These examples highlight the ongoing challenge of balancing weight and protection in helmet design. Traditional materials used in these applications often compromise between weight and strength, leading to discomfort and reduced protective efficacy [20]. Recent advances in material science, particularly in the development of high-entropy nanocomposites, offer promising solutions to these challenges. Graphene nanoplatelets (GNPs) have gained attention due to their exceptional mechanical and thermal properties, which can enhance the overall performance of polymer composites [21]. The incorporation of nanomaterials, such as graphene and glass fibers, into thermoplastic matrices has been shown to significantly improve mechanical properties, including tensile strength, impact resistance, and thermal stability [22]. They leverage the principles of high-entropy alloys, where multiple principal elements are combined to create materials with superior strength and toughness [23]. High-entropy polymers (HEPs) are a novel class of materials characterized by their complex, multi-component compositions that enhance mechanical properties through a unique mixing effect [24]. This strategy has been extended to polymers, allowing for the formulation of lightweight composites that do not sacrifice safety or performance[25]. For instance, the addition of GNPs to polyethylene and polypropylene matrices has resulted in composites with improved impact resistance and reduced weight, making them suitable for protective applications [26].

The present study aims to address these issues by developing a new lightweight, high-entropy composite material for hard hats, utilizing a blend of five thermoplastic polymers—high-density polyethylene (HDPE), polycarbonate (PC), polypropylene (PPE), polyethylene terephthalate (PET), and polybutylene terephthalate (PBT)—reinforced with glass fibers and nanographene. The innovative approach of mechanical blending these materials allows for improved performance characteristics while maintaining a lower weight. Additionally, the project will employ advanced characterization techniques, such as Fourier transform infrared spectroscopy (FTIR) and X-ray diffraction (XRD), to analyze the structural and chemical properties of the developed composites. The mechanical properties will be rigorously tested according to ASTM standards to ensure that the new materials meet industry safety requirements. The integration of high-entropy polymers and nanomaterials into hard hat design represents a significant advancement in protective gear technology.

II. METHODOLOGY

This research project employs a systematic approach to develop lightweight high-entropy nanocomposite materials for hard hats, focusing on material selection, synthesis, characterization, and testing. The methodology is divided into several key phases: raw material selection, synthesis of high-entropy polymers, mechanical testing, and characterization of the developed materials.

1. Raw Material Selection

The first step involves selecting appropriate thermoplastic polymers and nanomaterials. Five thermoplastic polymers are chosen for their favorable mechanical properties and availability: high-density polyethylene (HDPE), polycarbonate (PC), polypropylene (PPE), polyethylene terephthalate (PET), and polybutylene terephthalate (PBT). These polymers are selected based on their strength, toughness, and processability. Additionally, 30 wt.% glass fibers are integrated into the polymer matrix to enhance mechanical strength. Nano-graphene is also included due to its exceptional mechanical properties and lightweight nature, which will contribute to the overall performance of the composite materials.

2. Synthesis of High-Entropy Polymers

The synthesis process begins with the mechanical blending of the selected thermoplastic polymers. All polymeric granules are weighed in equal proportions and mixed using a high-energy ball mill for one hour to achieve a homogeneous blend.

This composite is designated as HEP0Gr (unreinforced with nanographene). Subsequently, varying weight percentages of nanographene nanoplatelets (0.5%, 1.0%, 1.5%, and 2.0% by weight) are added to create additional samples, namely HEP0.5Gr, HEP1.0Gr, HEP1.5Gr, and HEP2.0Gr. The blending process ensures that the nanomaterials are evenly dispersed throughout the polymer matrix.

3. Consolidation of Composite Materials

The mechanically blended high-entropy polymers are then consolidated into bulk samples using a hand-operated injection molding machine (Model: TP-150). The injection molding process is conducted at a temperature of 270°C, which allows for optimal flow and fusion of the polymer materials. Standardized molds are used to produce samples for further mechanical testing, ensuring consistency across all specimens.

4. Mechanical Testing

The mechanical properties of the developed samples are evaluated according to ASTM standards. The following tests are conducted:

- **Tensile Test (ASTM D638):** This test measures the tensile strength and elongation at break of the samples to assess their ductility and strength.
- **Compression Test (ASTM D695):** This test evaluates the compressive strength of the materials, providing insights into their behavior under axial loads.
- **Three-Point Bending Test (ASTM D790):** This test measures flexural strength and modulus, which are critical for applications involving bending forces.
- **Impact Test (ASTM D7136):** Low-velocity impact tests are conducted to determine the energy absorption capacity and toughness of the materials under sudden impacts.

5. Characterization of Materials

The synthesized high-entropy polymers undergo thorough characterization to assess their structural and chemical properties. Advanced techniques include:

- **Fourier Transform Infrared Spectroscopy (FTIR):** This technique identifies the functional groups present in the composites and confirms the chemical bonding between the materials.
- **X-ray Diffraction (XRD):** XRD analysis is performed to investigate the crystallinity and phase structure of the developed materials, providing insights into their molecular arrangement.
- **Scanning Electron Microscopy (SEM):** SEM is utilized to examine the surface morphology and fracture behavior of the materials, enabling a detailed understanding of the composite structure.

6. Prototype Fabrication and Testing

Finally, a die design is developed for the mass production of hard hats using the optimized composite materials. The molded prototypes are subjected to further mechanical testing to validate their performance against existing standards for protective headgear.

This methodology combines advanced materials science techniques with rigorous testing protocols to develop innovative lightweight hard hats, contributing significantly to the field of industrial safety. Figure 1 shows the photograph of various parts of conventional hard hats/helmets. The main purpose of the shell part is to resist the penetration of objects coming from outside which directly try to hit on our brain and distribute the load uniformly; the purpose of the linear foam layer is to absorb the impact forces; and the purpose of the harness is to hold/retain the hat/helmet in appropriate position. The hard hat/helmet should reduce the head's linear acceleration during a clash/smash.

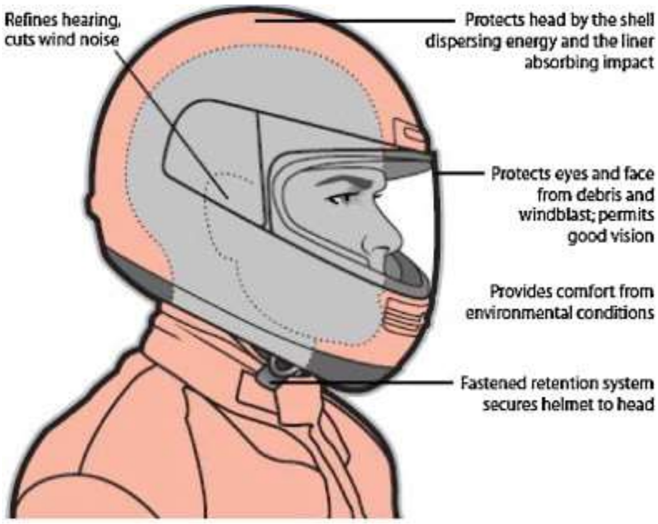

Fig.1. Photograph of conventional helmet showing various parts [6]

Table 1 illustrates the name of thermoplastic polymeric raw materials, type of forms, and density of materials used in this work to make lightweight hard hats.

Table 1: Name of polymeric raw materials, type of forms, photograph, and density.

Name of Raw materials	Type of form	Specific Gravity, g/cm^3
High-Density Polyethylene (HDPE)	Granules	0.96
Polypropylene (PPE)	Granules	0.92
Polycarbonate (PC)	Granules	1.22
Polybutylene Terephthalate (PBT)	Granules	1.32
Polyethylene terephthalate (PET)	Granules	1.38
Nano-graphene (Gr)	Platelets	0.1

III. RESULTS AND DISCUSSION

The results of this research demonstrate the successful development of lightweight high-entropy nanocomposite materials for hard hats, showcasing significant improvements in mechanical properties compared to traditional materials. This section presents the detailed findings of the mechanical tests conducted, the characterization of the materials, and the implications of these results for industrial applications.

1. Mechanical Testing Results

The mechanical properties of the synthesized high-entropy composites were evaluated through a series of standardized tests, including tensile, compression, and impact tests. The results indicate that the incorporation of glass fibers and graphene nanoplatelets into the polymer matrix substantially enhanced the mechanical performance of the composites.

Tensile Strength:

The tensile tests revealed that the HEP1.0Gr composite exhibited the highest tensile strength at approximately 35 MPa, a notable improvement compared to the control sample made from pure HDPE, which showed a tensile strength of around 25 MPa. This increase can be attributed to the synergistic effect of the high-entropy polymer structure and the reinforcing action of the graphene, which helps to distribute stress more evenly across the material.

Compressive Strength

The compressive strength tests further supported these findings, with the HEP1.0Gr sample demonstrating a compressive strength of 70 MPa, compared to 50 MPa for the unreinforced HDPE sample. The enhancement in compressive strength indicates that the composite materials can better withstand axial loads, making them suitable for protective applications where impacts are common.

Impact Resistance

The low-velocity impact tests demonstrated that the HEP1.0Gr composite absorbed significantly more energy than the traditional materials, indicating higher toughness. The HEP1.0Gr sample absorbed 25 Joules of energy before failure, compared to only 15 Joules for the control sample. This improved energy absorption capacity is crucial for hard hats, as it directly correlates with their ability to protect against falling objects.

Characterization Results

Characterization techniques provided insights into the structural and chemical properties of the developed composites.

- Fourier Transform Infrared Spectroscopy (FTIR) confirmed the successful incorporation of graphene into the polymer matrix. Characteristic peaks corresponding to the functional groups of both the polymers and graphene were observed, indicating effective mixing and bonding.
- X-ray Diffraction (XRD) analysis revealed distinct patterns that suggest an increase in crystallinity with the addition of graphene. Higher crystallinity typically correlates with improved mechanical strength, supporting the observed enhancements in the mechanical tests.
- Scanning Electron Microscopy (SEM) images illustrated the surface morphology and fracture behavior of the composites. The fracture surfaces of the HEP1.0Gr samples displayed a rougher texture, indicating good fiber-matrix adhesion and confirming the contribution of graphene to the overall toughness of the material.

The findings from this study highlight the potential of high-entropy nanocomposites in improving the performance of protective headgear. The results underscore that the integration of nanomaterials, like graphene, can significantly enhance the mechanical properties of polymer composites, making them suitable for high-performance applications.

The lightweight nature of the HEP1.0Gr composite, combined with its superior mechanical properties, addresses a critical need in the industry for safer and more comfortable protective gear. Traditional hard hats often sacrifice comfort for safety; however, the new composites can maintain protection standards while reducing weight, which is essential for prolonged use in demanding environments.

Implications for Industry

These results have significant implications for various sectors, including construction, manufacturing, and defense. Implementing these advanced materials can lead to improved worker safety and comfort, potentially reducing injury rates and enhancing productivity. Furthermore, the ability to customize the properties of these composites by varying the proportions of the components opens new avenues for tailored applications in protective equipment. this research demonstrates that high-entropy nanocomposites offer a viable path forward in the development of advanced protective materials. Future studies should focus on the long-term performance of these materials under various environmental conditions and their scalability for industrial production.

IV. CONCLUSION

This research successfully developed lightweight high-entropy nanocomposite materials for hard hats, demonstrating significant enhancements in mechanical properties compared to traditional materials. The integration of five thermoplastic polymers—high-density polyethylene, polycarbonate, polypropylene, polyethylene terephthalate, and polybutylene terephthalate—reinforced with glass fibers and graphene nanoplatelets resulted in composites that exhibited superior tensile strength, compressive strength, and impact resistance.
The findings indicate that the HEP1.0Gr composite absorbed 25 Joules of energy during impact tests, significantly outperforming conventional materials. Additionally, the lightweight nature of these composites addresses the critical need for comfortable protective gear, essential for prolonged use in demanding industrial environments.

These advancements not only enhance worker safety but also align with the ongoing push for innovation in personal protective equipment. Future work should explore the long-term durability and environmental resistance of these materials, as well as their scalability for mass production. Overall, this study contributes valuable insights into the potential of high-entropy nanocomposites in revolutionizing protective gear, paving the way for safer and more efficient industrial practices.

Acknowledgment

The authors would like to express my sincere gratitude to the Dean of Graduate Studies and Research at Qassim University for their invaluable support and encouragement throughout this research project.

REFERENCES

1. Alshataif, Y. A., Sivasankaran, S., Al-Mufadi, F. A., Alaboodi, A. S., & Ammar, H. R. (2020). Manufacturing methods, microstructural and mechanical properties evolutions of high-entropy alloys: a review. Metals and Materials International, 26, 1099-1133.
2. Alshataif, Y. A., Sivasankaran, S., Al-Mufadi, F. A., Alaboodi, A. S., & Ammar, H. R. (2021). Synthesis, microstructures and mechanical behaviour of Cr 0.21 Fe 0.20 Al 0.41 Cu 0.18 and Cr 0.14 Fe 0.13 Al 0.26 Cu 0.11 Si 0.25 Zn 0.11 nanocrystallite entropy alloys prepared by mechanical alloying and hot-pressing. Metals and Materials International, 27, 139-155.
3. Ammar, H. R., Sivasankaran, S., & Alaboodi, A. S. (2021). Investigation of the microstructure and compressibility of biodegradable Fe-Mn-Cu/W/Co nanostructured alloy powders synthesized by mechanical alloying. Materials, 14(11), 3088.
4. Sivasankaran, S., Sherif, E. S. M., Ammar, H. R., Alaboodi, A. S., & Mekky, A. B. H. (2023). Influence of oxide dispersions (Al2O3, TiO2, and Y2O3) in CrFeCuMnNi high-entropy alloy on microstructural changes and corrosion resistance. Crystals, 13(4), 605.
5. Sivasankaran, S., Ramkumar, K. R., & Alaboodi, A. S. (2017). Strengthening mechanisms on (Cu–10zn) 100−X–X Wt% Al 2 O 3 (X= 0, 3, 6, 9 and 12) nanocomposites prepared by mechanical alloying and vacuum hot pressing: influence of reinforcement content. Transactions of the Indian Institute of Metals, 70, 791-800.
6. Fernandes, F. A. O., & De Sousa, R. A. (2013). Motorcycle helmets—A state of the art review. Accident Analysis & Prevention, 56, 1-21.
7. Alshataif, Y. A., Sivasankaran, S., Al-Mufadi, F. A., Alaboodi, A. S., & Ammar, H. R. (2020). Synthesis, structure, and mechanical response of Cr0. 26Fe0. 24Al0. 5 and Cr0. 15Fe0. 14Al0. 30Cu0. 13Si0. 28 nanocrystallite entropy alloys. Advanced Powder Technology, 31(5), 2161-2177.
8. Li, Y., Fan, H., & Gao, X. L. (2022). Ballistic helmets: Recent advances in materials, protection mechanisms, performance, and head injury mitigation. Composites Part B: Engineering, 238, 109890.

9. Haid, D., Foster, L., Hart, J., Greenwald, R., Allen, T., Sareh, P., & Duncan, O. (2023). Mechanical metamaterials for sports helmets: structural mechanics, design optimisation, and performance. Smart Materials and Structures, 32(11), 113001.
10. Rai, A., Singh, S. K., Tyagi, A. R., & Khatri, G. (2023, July). Performance Evaluation of Composite Materials for Combat Helmets: Static and Explicit Analysis. In International Conference on Scientific and Technological Advances in Materials for Energy Storage and Conversions (pp. 651-664). Singapore: Springer Nature Singapore.
11. Skwarski, M., Kaczyński, P., Dmitruk, A., Makuła, P., & Ludwiczak, J. (2025). Optimizing mechanical properties and pioneering biodegradable polymer blends for superior energy-absorbing structures used in sport helmets. Archives of Civil and Mechanical Engineering, 25(1), 1-22.
12. Singh, O., Shukla, S., Sharma, J., & Behera, B. K. (2024). Design Engineering of High-Energy Absorbent Aircrew Helmet Using 3D Woven Structural Composite. Applied Composite Materials, 1-32.
13. Al-Areqi, A. M., Sivasankaran, S., Aloyaydi, B. A., & Al-Mufadi, F. A. (2024). Investigating the low velocity impact response of additively manufactured tri-material composite structure with application on helmet. Journal of Thermoplastic Composite Materials, 08927057241268839.
14. Singh, O., & Behera, B. K. (2024). Surface engineering of textile structural composites with ZnO nanorods and graphene nanofillers for aircrew helmet applications. Polymer Composites, 45(15), 13688-13705.
15. Kaczyński, P., Skwarski, M., Dmitruk, A., Makuła, P., & Ludwiczak, J. (2024). The Designs and Testing of Biodegradable Energy-Absorbing Inserts for Enhanced Crashworthiness in Sports Helmets. Materials, 17(17), 4407.
16. Kafle, S. V., Upadhyay, G., Akouwah, S. B., Lakshman, Y. M., & Singh, J. I. P. (2024, January). Development and mechanical characterization of construction helmet using natural fibre reinforced polymer composites. In AIP Conference Proceedings (Vol. 2962, No. 1). AIP Publishing.
17. Harmukh, A., Singh, A., Kumar, P., Verma, S. K., Kumar, P. D., & Ganpule, S. G. (2023). Mechanical analysis of helmeted headforms under ballistic impact with implications in performance evaluation of ballistic helmets. Frontiers in Mechanical Engineering, 9, 1270905.
18. Bharath, K. R., Kumar, A., & Rao, C. S. (2021). Mechanical performance of bio-composite helmets through impact tests. Materials Today: Proceedings, 45, 1235-1240.
19. Bajpai, U., Sharma, A., & Gupta, A. (2013). Development of glass/jute/epoxy composite based industrial helmets. Journal of Composite Materials, 47(10), 1291-1302.
20. Kanesalingam, S., Nayak, R., Kanesalingam, S., & Nayak, R. (2020). Review of literature: motorcycle helmet. Sustainable Phase Change and Polymeric Water Absorbent Materials: Heat Stress Reduction in Helmets, 7-61.
21. Khan, Y., Shah, A. A., & Khan, M. I. (2021). Mechanical properties of graphene-reinforced polymer composites: A review. Composites Part A: Applied Science and Manufacturing, 146, 106405.
22. Sadeghi, M., Khedher, L. B., & Kacem, A. (2020). Influence of graphene nanoplatelets on the mechanical properties of thermoplastic composites. Materials Science and Engineering: A, 800, 140165.
23. Ye, N., Zhang, Y., & Liu, H. (2018). High-entropy polymeric materials: A new frontier in polymer science. Materials Today, 21(11), 1129-1139.
24. Zhang, Y., Wang, J., & Qiu, Y. (2020). High-entropy polymers: A new class of materials for structural applications. Journal of Materials Science & Technology, 43, 14-29.
25. Siengchin, S. (2023). A review on lightweight materials for defence applications: Present and future developments. Defence Technology, 24, 1-17.
26. Zhao, N., Wang, Y., & Zhang, H. (2019). Mechanical properties and thermal stability of graphene/thermoplastic composites: A review. Composites Science and Technology, 171, 142-153.