

ORIGINAL ARTICLE

Effect of Multi-Walled Carbon Nanotube (MWCNT) Diameter on the Adaptive Impact Response and Energy Absorption of Shear Thickening Fluid-Impregnated Polyurethane Foam

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ABSTRACT – Lightweight polyurethane foam is widely used for impact protection, but its performance remains limited under high-energy loading because of unstable cell collapse and rapid force transmission. To address this limitation, this study investigates polyurethane foam impregnated with a polyethylene glycol 400 (PEG 400)- silica (SiO₂)-based shear thickening fluid (STF) containing 1.2 wt.% multi-walled carbon nanotubes (MWCNTs) with different diameter ranges of 8–15, 10–30, and 20–40 nm to identify the most effective formulation for adaptive impact mitigation. Rheological testing showed that all STF systems exhibited shear-thickening behavior, while the 20–40 nm MWCNT formulation produced the earliest thickening onset, at around 100 s⁻¹, and the highest peak viscosity, approximately 220 Pa·s. Under drop-impact loading of 200–1200 g and 1.0–1.5 m, the corresponding impregnated foam (PF+S3) exhibited the most compact morphology, the most stable force-time response, the longest impact duration, and the highest impulse under the highest impact condition, indicating the most effective momentum absorption and energy dissipation. Scanning electron microscopy–energy dispersive X-ray (SEM-EDS) observations further confirmed improved STF retention and more homogeneous silica-rich distribution within the foam structure. These results show that the superior performance of PF+S3 was not governed only by densification but also by the diameter-dependent effects of MWCNTs on STF connectivity, load transfer, hydro cluster formation, and damping behavior. The findings demonstrate that MWCNT diameter is a critical parameter in designing STF-reinforced polyurethane foam for lightweight adaptive impact-protection applications.

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INTRODUCTION

Polyurethane foam (PF) is widely used as a lightweight energy-absorbing material in protective systems because of its low density, cellular architecture, and ability to undergo large deformation under impact loading. However, its impact-mitigation performance remains limited under high-energy or repeated loading conditions. Under dynamic compression, PF tends to experience localized cell collapse, non-uniform deformation, and damage-zone propagation, which reduce structural stability and increase the transmitted peak force [1]. Its response is also strongly governed by microstructural features such as pore size, pore distribution, and cell-wall thickness; irregular pore morphology and weak cell walls generally lead to premature densification and reduced energy absorption efficiency [2], [3]. In addition, PF is sensitive to strain rate and environmental exposure, including temperature and moisture, which can further degrade its consistency and mechanical reliability in demanding applications [4]–[6]. Therefore, improving the dynamic load distribution and adaptive impact response of PF remain important challenges in the design of protective materials.

One promising approach to overcoming these limitations is impregnation with a shear thickening fluid (STF). STF behaves as a fluid-like medium under low shear but rapidly increases in viscosity under sudden loading, enabling temporary stiffening and improved impact resistance [7]. Previous studies have shown that STF impregnation can enhance the energy absorption of several porous and flexible systems, including natural rubber foam, ultra-high-molecular-weight polyethylene (UHMWPE)-based structures, auxetic systems, and metallic foams [8]–[10]. A recent study by Hu et al. [11] further demonstrated that STF-filled lattice structures can improve dynamic response and energy absorption, reinforcing the broader potential of STF-assisted architectures for impact-protection applications. In parallel, nanoparticle-modified STF systems containing graphene-based fillers, nano silica, and carbon nanomaterials have been reported to exhibit higher peak viscosity, lower critical shear rate, and improved load-bearing capability under dynamic loading [7], [12], [13].

Among the available nanofillers, multi-walled carbon nanotubes (MWCNTs) are particularly attractive because of their high aspect ratio, large specific surface area, excellent stiffness, and ability to form interconnected load-transfer networks in composite systems. MWCNT incorporation has been reported to improve tensile, flexural, fracture, and impact properties in a wide range of polymer composites when dispersion is properly controlled [14], [15]. In STF systems, MWCNTs are also expected to promote particle-particle interactions, strengthen transient shear-induced networks, and modify rheological behavior by facilitating stress transfer and hydrocluster development [13], [16], [17]. However, the effectiveness of MWCNTs strongly depends on dispersion quality, as agglomeration can disrupt network uniformity and reduce composite performance [18], [19].

Recent developments in foam-based impact materials have also emphasized that energy absorption is governed not only by the base polymer but also by structural design and multiscale reinforcement. Functionally graded architectures, hybrid cellular systems, and nanoparticle-stabilized foams have all been shown to improve deformation control and structural stability under dynamic loading [20]. Recent studies have also reported that the energy absorption of polyurethane foam can be further improved through material and structural modification strategies, confirming the strong potential of foam-based systems for impact-mitigation applications [21]. Nevertheless, previous solutions still leave important questions unanswered for STF-impregnated PF. Most reported studies focus either on improving the rheological performance of STF or on reinforcing dense laminates and sandwich structures, rather than porous polyurethane foam with its distinct cell-collapse and fluid-structure interaction mechanisms [22]–[25]. In addition, the reasons why certain STF formulations are more effective in porous foams remain insufficiently discussed, particularly regarding stress redistribution, damping behavior, and energy dissipation during impact.

A key unresolved issue is the role of MWCNT diameter in STF-impregnated PF. Although MWCNT-containing STF has been reported to improve impact resistance and reduce the critical shear rate, prior studies generally discuss MWCNT addition in a broad sense and do not isolate the effect of nanotube diameter on the impact response of porous PF [23], [24]. This limitation is important because nanotube diameter can influence aspect ratio, dispersion quality, interparticle bridging, and the formation of load-transfer pathways within the STF-filled foam structure [16], [18], [19]. Furthermore, previous studies have rarely linked the post-impregnation morphology of PF with dynamic impact metrics such as maximum force, impact period, and impulse under systematically varied masses and drop heights. As a result, the interaction among PF cellular structure, STF rheological behavior, and MWCNT geometry remains insufficiently understood. This gap directly motivates the present study and more clearly positions it within current efforts to improve the impact performance of polyurethane foam systems.

Accordingly, this study investigates the adaptive energy absorption behavior of PF impregnated with polyethylene glycol 400 (PEG 400)-silica (SiO_2)-based STF reinforced with MWCNTs of different diameter ranges (8–15 nm, 10–30 nm, and 20–40 nm). PEG- SiO_2 was selected as the STF matrix because it is a well-established shear thickening system, while MWCNTs were incorporated to modify the particle interaction network and potentially improve load transfer and impact-adaptive stiffening under dynamic loading [7], [16]. The novelty of this work lies in the integration of porous PF with MWCNT-modified STF and the systematic evaluation of diameter-dependent behavior through drop-impact testing under different masses and drop heights. By correlating maximum force, impact period, impulse, and foam morphology, this study aims to clarify how nanotube diameter influences the dynamic response and energy absorption capability of STF-impregnated PF, thereby providing a more focused basis for the design of adaptive protective foam systems.

EXPERIMENTAL METHOD

Materials and Instruments

The main matrix material used in this study was polyurethane foam (PF) obtained from a marketplace in Indonesia. As a reinforcing material, 20 nm nanosilica particles purchased from Hebei Suoyi, China, were used. Multi-walled carbon nanotubes (MWCNTs) were obtained from XF Nano, China. The MWCNTs used had outer diameters ranging from 8–15 nm, 10–30 nm, and 20–40 nm. Additional materials used in the shear thickening fluid (STF) manufacturing process included ethanol (99.8%) and polyethylene glycol 400 (PEG400) with analytical purity obtained from Sigma-Aldrich.

Method and Procedure

Preparation of STF

Shear thickening fluid (STF) was prepared by mixing 30% silica (SiO_2) into polyethylene glycol 400 (PEG400) using a high-speed mixer at a speed of 3000 rpm for 60 minutes. After homogeneous mixing, MWCNT was added at a concentration of 1.2%, with particle sizes of 8–15 nm, 10–30 nm, and 20–40 nm. The resulting suspension was then further processed using a 150 W probe-type sonicator for 30 minutes to ensure uniform dispersion of MWCNT in the PEG400- SiO_2 matrix (Figure 1).

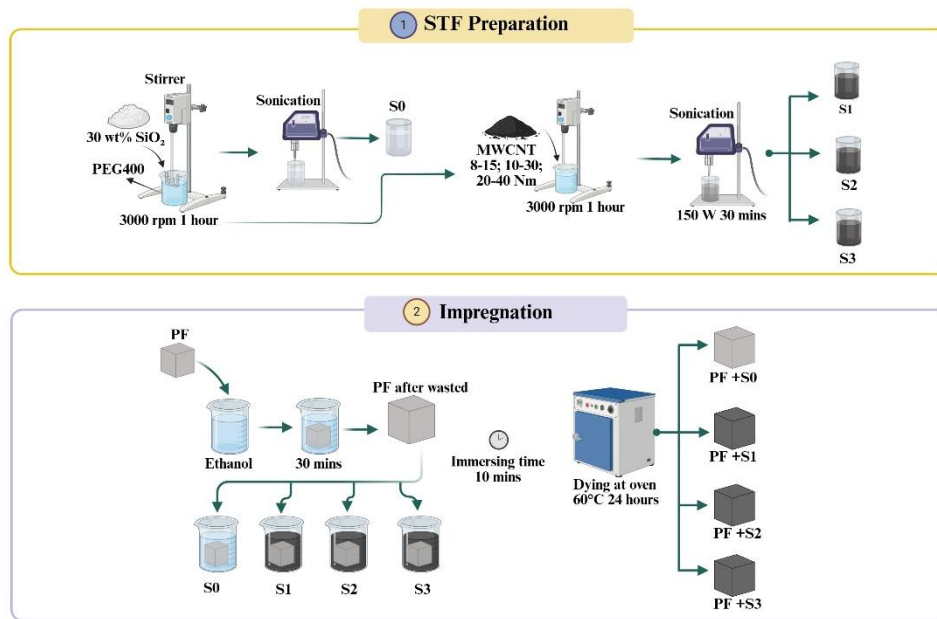


Figure 1. Preparation of MWCNT-modified shear thickening fluid and impregnation of polyurethane foam

STF Impregnation on PF

The impregnation process begins with preparing polyurethane foam (PF) cut into $50 \times 50 \times 50$ mm cubes. The PF samples were then immersed in ethanol for 30 minutes to remove surface impurities and improve the wettability of the foam prior to STF impregnation. This process aims to modify the foam surface to make it more active in accepting the STF liquid.

After the cleaning process is complete, the PF samples are immediately dipped in the prepared multiphase STF liquid and left for 10 minutes. This immersion time was chosen so that the STF could soak in and spread evenly into the PF pore structure. This impregnation process was important to ensure that the entire internal volume of the PF was homogeneously filled with STF, so that consistent material distribution was achieved and mechanical and rheological performance could be optimized (Figure 1).

After impregnation, the STF-impregnated PF samples were dried in an oven at 60°C for 24 hours. This heating process aimed to remove any ethanol residue remaining in the PF structure from the previous cleaning process. In addition, this heating also ensured the permanent adhesion of STF to the PF network, resulting in a stable composite ready for the next testing stage. The composition of PF samples impregnated with STF at various MWCNT concentrations is shown in Table 1, and the results are shown in Figure 2.

Table 1. Composite of polyurethane foam and STF/MWCNT-impregnated foam samples

Code	STF		MWCNT	
	PEG 400	SiO ₂ (Wt%)	Size (Nm)	Weight (g)
PF	-	-	-	-
PF+S0	Balanced	30	-	0
PF+S1		30	8–15	1.2
PF+S2		30	10–30	1.2
PF+S3		30	20–40	1.2

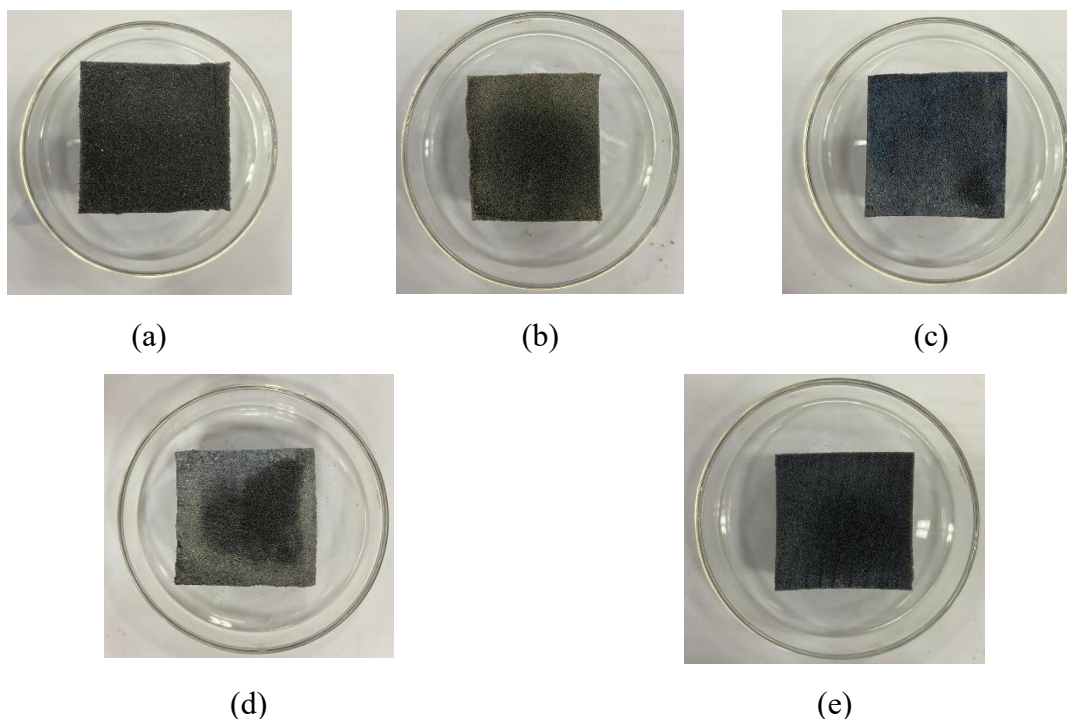


Figure 2. Photographs of the prepared polyurethane foam samples: (a) PF, (b) PF+S0, (c) PF+S1, (d) PF+S2, and (e) PF+S3

Density and Porosity Measurement

The apparent density of the foam was calculated from the sample mass-to-volume ratio.

$$\rho = \frac{m}{V} \quad (1)$$

where ρ is the apparent density, m is the sample mass, and V is the bulk volume. The porosity was then determined using:

$$\phi = \left(1 - \frac{\rho_{foam}}{\rho_{solid}}\right) \times 100\% \quad (2)$$

where ϕ is the porosity, ρ_{foam} is the apparent density of the foam, and ρ_{solid} is the density of the solid matrix. These parameters were used to evaluate the structural effect of STF impregnation on the foam. All measurements were conducted on at least $n = 3$ specimens for each condition, and the results are reported as mean $\pm$ standard deviation.

STF Uptake Calculation

The STF uptake was determined gravimetrically from the mass difference before and after impregnation using:

$$STF \text{ uptake (\%)} = \frac{m_f - m_0}{m_0} \times 100 \quad (3)$$

where m_0 is the initial dry mass of the foam and m_f is the dry mass after impregnation and oven drying. This parameter was used to quantify the amount of STF retained within the foam structure.

Rheology

The rheology of STF was characterized using a Thermo Scientific Haake Mars III Rheometer with a 50 mm radius conical plate and a 1° angle. Testing was conducted at room temperature in steady-flow mode, and the viscosity of STF was measured over a shear rate range of $0.1\text{--}1000 \text{ s}^{-1}$. The rheological data were used to evaluate shear thickening behavior and compare the viscosity responses of STF and STF/MWCNT systems.

Drop Test

Impact testing was conducted by dropping weights (Figure 3) with masses of 200 g, 400 g, 600 g, and 1200 g from heights of 1, 1.25, and 1.5 m. Each PF sample was placed on a flat surface, and a load cell (Zemic L6E-3, capacity 5 kN, accuracy $\pm 0.5\%$ FS) was positioned underneath it to measure the impact force received. The force measured during this impact test was then analyzed to evaluate the energy absorption performance of the foam samples.

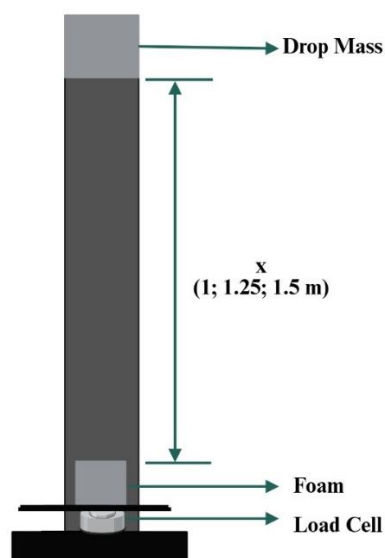


Figure 3. Drop test schematic

Morphology and Elemental Analysis

The morphology of the samples was analyzed using a Hitachi TM4000 Plus scanning electron microscope (SEM) with an acceleration voltage of 20 kV to analyze the surface characteristics and microstructure of the samples after the impregnation and impact test processes. The elemental distribution in the sample was observed using energy dispersive X-ray spectroscopy (EDS, Bruker QuantaX) at a voltage of 20 kV, a current of 8 μ A, and a working distance of 9.5 mm with a lifetime of 50 seconds.

RESULT AND DISCUSSION

Morphology and Pore Characteristics

Figure 4 shows the scanning electron (SEM) morphology of neat polyurethane foam (PF) and *shear thickening fluid/multi-walled carbon nanotube* (STF/MWCNT)-impregnated foams after drop testing at 30 $\times$ and 100 $\times$ magnification. In neat PF, the cellular structure appears more irregular, with larger open pores and more visible cell-wall damage after impact. This indicates that the untreated foam absorbed energy mainly through local structural collapse, resulting in limited resistance to impact loading. In contrast, the impregnated foams show a denser and more stable cellular structure, indicating that the STF phase helped maintain the integrity of the foam framework during impact. Such behavior is consistent with previous studies showing that STF impregnation can improve structural stability and dynamic energy absorption [10], [13].

At 30 $\times$ magnification, PF+S0 already shows partial filling of the pore network compared with neat PF, confirming that the polyethylene glycol 400 (PEG 400)-silica (SiO_2)-based shear thickening fluid (STF) was retained inside the foam structure. However, the multi-walled carbon nanotube (MWCNT)-containing foams exhibit a more distinct morphological improvement. PF+S1 shows a denser structure than PF+S0, but particle-rich regions are still locally concentrated. PF+S2 and PF+S3 display a more compact and homogeneous pore structure, with fewer large open pores and better-preserved cell walls. Among all samples, PF+S3 shows the most uniform morphology, indicating that the 20–40 nm MWCNTs provide the most effective connectivity within the STF-rich phase. This observation addresses the reviewer's request to explain how larger MWCNT diameters can result in a more effective connection between silica particles. At 100 $\times$ magnification, the difference becomes clearer. The neat PF sample shows more severe local wall damage, whereas the impregnated foams exhibit silica-rich deposits attached to the cell walls. In PF+S1, these deposits are more clustered, indicating less uniform distribution. In PF+S2 and especially PF+S3, the deposited phase is distributed more continuously along the cell walls, suggesting better STF retention and a more effective load-transfer pathway during impact. This more continuous phase is important because it can delay local pore collapse and redistribute the applied load more evenly throughout the foam structure [13], [23], [25].

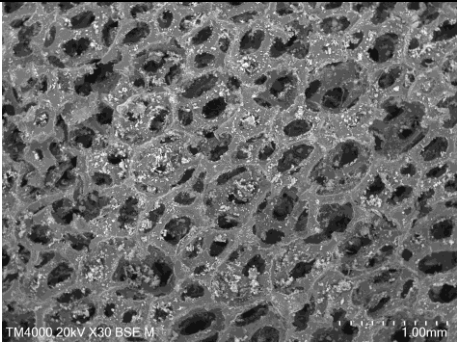
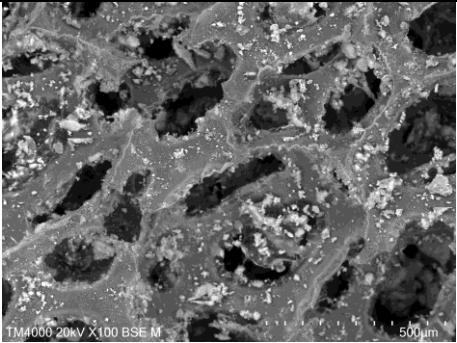
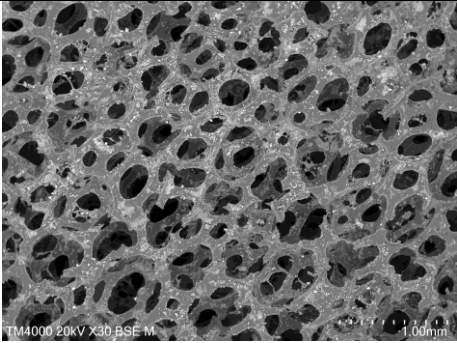
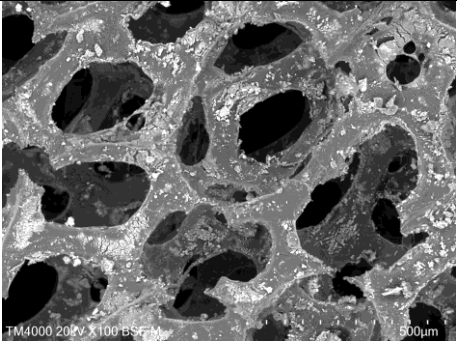
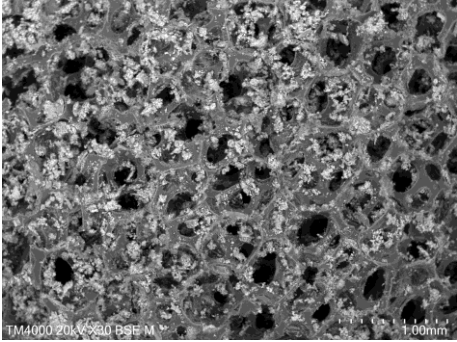
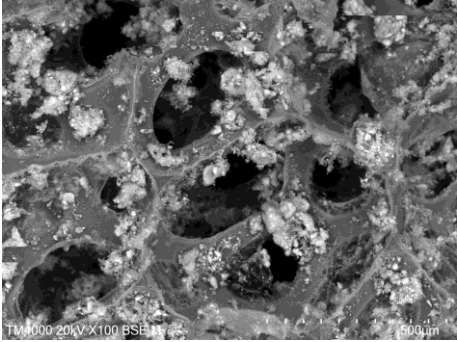
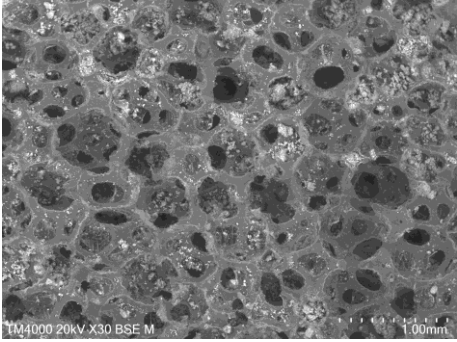
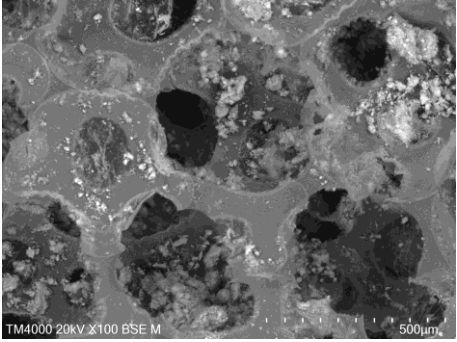
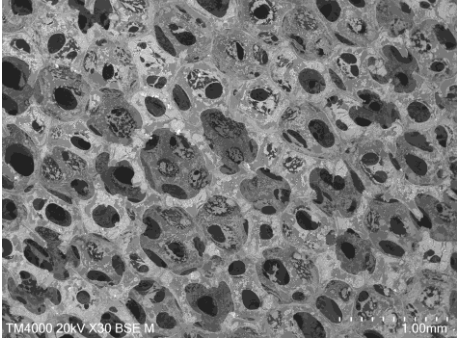
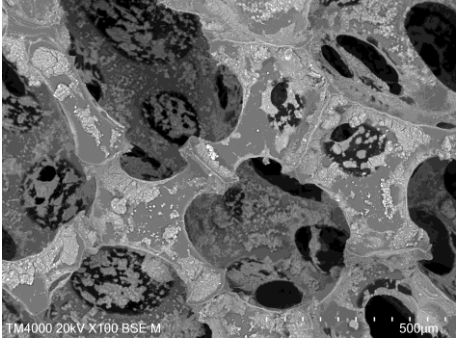
Sample	30× magnification	100× magnification
PF		
PF+S0		
PF+S1		
PF+S2		
PF+S3		

Figure 4. SEM images for foam after the drop test with different magnifications

The energy dispersive X-ray (EDS) results in Table 2 support the SEM observations. Compared with neat PF, all impregnated samples show higher silicon (Si) and oxygen (O) contents, confirming the presence of polyethylene glycol 400 (PEG 400)-silica (SiO_2)-based STF within the foam structure. The increase in Si content from PF to the STF/MWCNT-treated foams indicates successful silica uptake in the pore network, while the more pronounced Si-rich phase in PF+S2 and PF+S3 is consistent with their denser and more homogeneous morphology. This suggests that larger-diameter MWCNTs improved silica-particle connectivity and promoted a more stable STF distribution within the foam. As a result, the PF+S3 structure was better able to maintain cell-wall integrity under impact, which explains its superior damping and force attenuation behavior. This interpretation is also consistent with the density results, although the quantitative density discussion is presented separately.

Table 2. Energy-dispersive X-ray spectroscopy (EDS) results for neat and shear thickening fluid/multi-walled carbon nanotube STF/MWCNT after drop testing

Sample	C	O	Si	Fe
PF	74.24	24.98	0.22	0.56
PF+S0	52.08	37.95	9.29	0.68
PF+S1	43.75	42.06	13.42	0.77
PF+S2	39.86	44.58	14.81	0.75
PF+S3	36.94	46.39	15.98	0.69

However, the SEM–EDS results should be interpreted as microstructural evidence of STF retention and distribution, rather than as the sole proof of reinforcement. Therefore, the role of MWCNT diameter in improving impact performance must be discussed together with the rheological and impact-response results in the following sections.

Apparent Density, Apparent Porosity, and Estimated STF Uptake

Table 3 shows that neat PF had the lowest apparent density, $0.067 \pm 0.00111 \text{ g/cm}^3$, confirming the highly porous nature of the initial foam structure. After STF impregnation, the density increased markedly to $0.298 \pm 0.01000 \text{ g/cm}^3$ for PF+S0, indicating substantial retention of the STF phase within the pore network. After MWCNT addition, the density decreased to 0.216 ± 0.01060 , 0.231 ± 0.00551 , and $0.220 \pm 0.00564 \text{ g/cm}^3$ for PF+S1, PF+S2, and PF+S3, respectively. Using a density-based estimation, the apparent porosity of neat PF was 94.42%, while the impregnated samples showed lower apparent porosity, reflecting partial filling of the pore structure after STF impregnation.

Table 3. Apparent density, porosity of neat, and impregnated foams

Sample	Apparent density (g/cm^3)	Apparent porosity (%)	Estimated STF uptake (%)
PF	0.067 ± 0.00111	94.42	0.00
PF+S0	0.298 ± 0.01000	75.17	344.78
PF+S1	0.216 ± 0.01060	82.00	222.39
PF+S2	0.231 ± 0.00551	80.75	244.78
PF+S3	0.220 ± 0.00564	81.67	228.36

The estimated STF uptake values also showed a clear difference among the impregnated samples. PF+S0 exhibited the highest estimated uptake, whereas the MWCNT-containing samples showed lower but still substantial uptake. This indicates that the superior impact-related performance of PF+S3 was not governed simply by higher retained mass or densification. Although PF+S0 was the densest sample and showed the highest estimated uptake, PF+S3 exhibited better morphology, stronger rheological response, and more stable impact behavior. Therefore, the improved response of PF+S3 is better attributed to the diameter-dependent effect of MWCNT on STF distribution, silica-particle connectivity, and load transfer within the foam structure. This interpretation is consistent with previous studies showing that microstructural modification and filler-assisted STF reinforcement can influence impact performance beyond density alone [3], [13].

Rheological Behavior of STF/MWCNT Systems

Figure 5 shows that all STF systems exhibit shear-thickening behavior after an initial shear-thinning region. The neat STF (S0) has the lowest viscosity over the entire shear-rate range and shows the latest thickening onset, beginning at around $250\text{--}300\text{ s}^{-1}$, with a peak viscosity of about $50\text{ Pa}\cdot\text{s}$. After MWCNT addition, the viscosity increases markedly and the onset of thickening shifts to lower shear rates. S1 begins to thicken at around $200\text{--}250\text{ s}^{-1}$ and reaches a peak viscosity of about $60\text{ Pa}\cdot\text{s}$, whereas S2 thickens earlier at around $120\text{--}150\text{ s}^{-1}$ and reaches about $130\text{ Pa}\cdot\text{s}$. The strongest response is observed in S3, which shows the earliest thickening onset at around 100 s^{-1} and the highest peak viscosity, approximately $220\text{ Pa}\cdot\text{s}$.

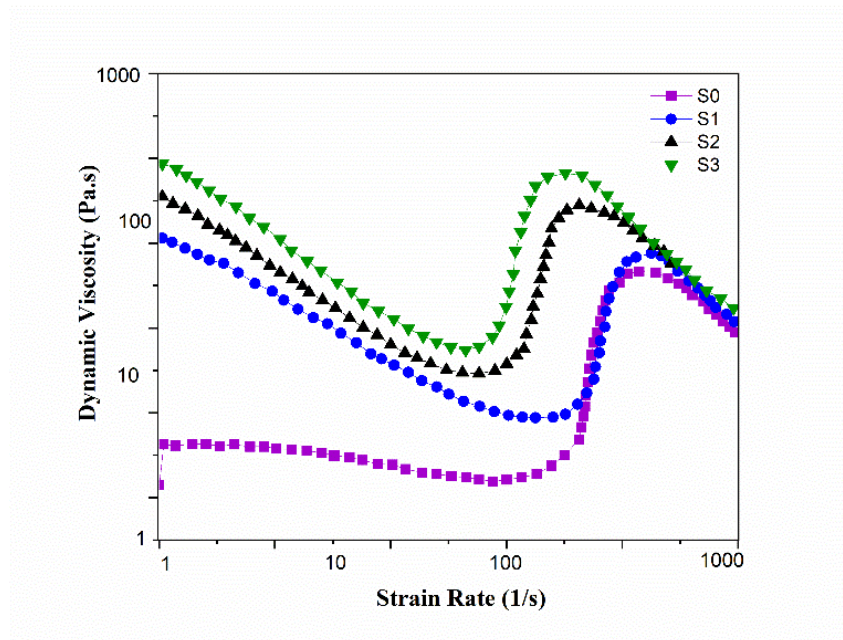


Figure 5. Rheology graph for different STF

This result indicates that increasing MWCNT diameter strengthened the rheological response of the STF by promoting earlier hydrocluster formation and stronger particle interaction under shear. As a result, the STF became more sensitive to dynamic loading and provided higher resistance to flow once the thickening onset was reached. The superior rheological behavior of S3 explains why the $20\text{--}40\text{ nm}$ MWCNT system also showed the most stable morphology and the best impact attenuation in the subsequent impact tests. Similar reductions in apparent critical shear rate and increases in peak viscosity after nanofiller addition have been reported in STF-based systems [13], [16], [17].

Peak Force and Force-Time Response Under Impact

Figure 6 shows that the maximum force increased as the impact mass increased from 200 to 1200 g and the drop height increased from 1.0 to 1.5 m . Among all samples, the MWCNT-containing foams showed higher force resistance than neat PF and PF+S0, with PF+S3 showing the highest peak-force response under the highest impact condition. This indicates that the addition of MWCNT improved the load-bearing response of the STF-impregnated foam. Figure 7 further shows that all samples exhibited a rapid force rise, followed by a peak and post-impact oscillation. Compared with neat PF, the STF-impregnated foams showed smoother force profiles and lower oscillation intensity. This effect became more evident after the addition of MWCNT, especially in PF+S2 and PF+S3.

Among all samples, PF+S3 showed the most stable force-time response, indicating better damping and more effective load redistribution during impact. The variation in curve shape at different impact levels is attributed to the heterogeneous collapse of the foam cells and the non-uniform distribution of STF within the porous structure. Therefore, the force profile reflects not only peak-force resistance, but also the ability of the foam to control force transmission during dynamic loading. This more controlled response is consistent with previous reports that MWCNT-modified STF systems improve impact damping and load-transfer behavior [13], [23].

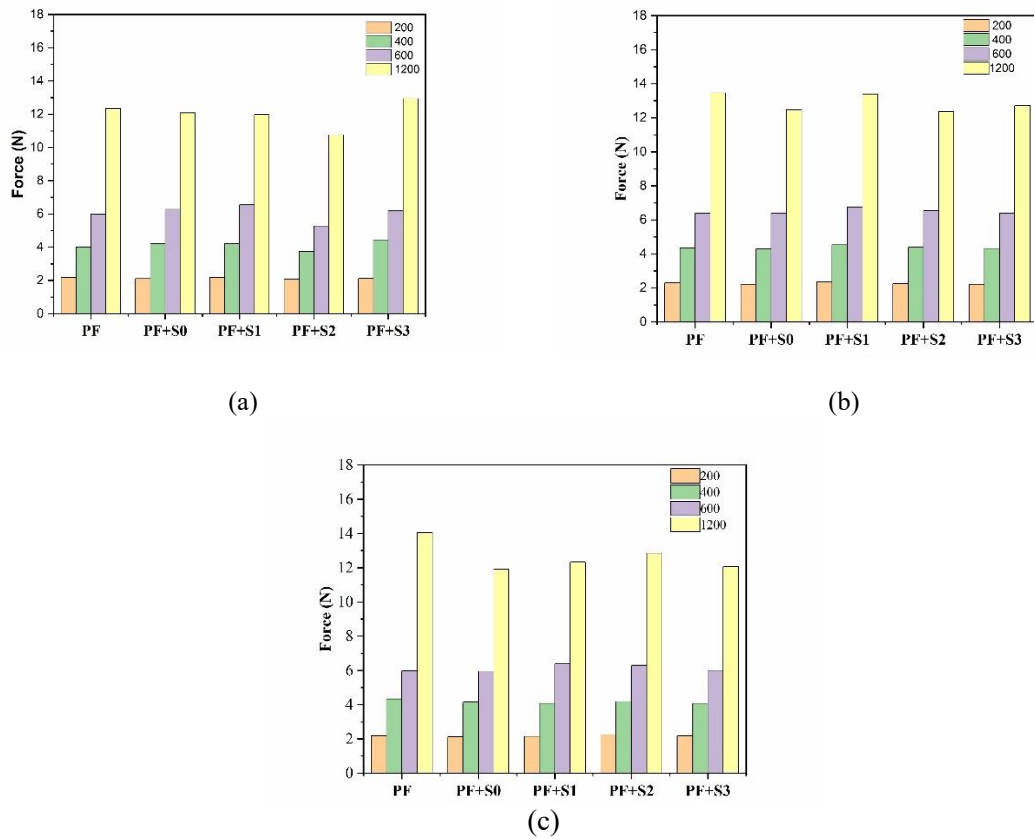
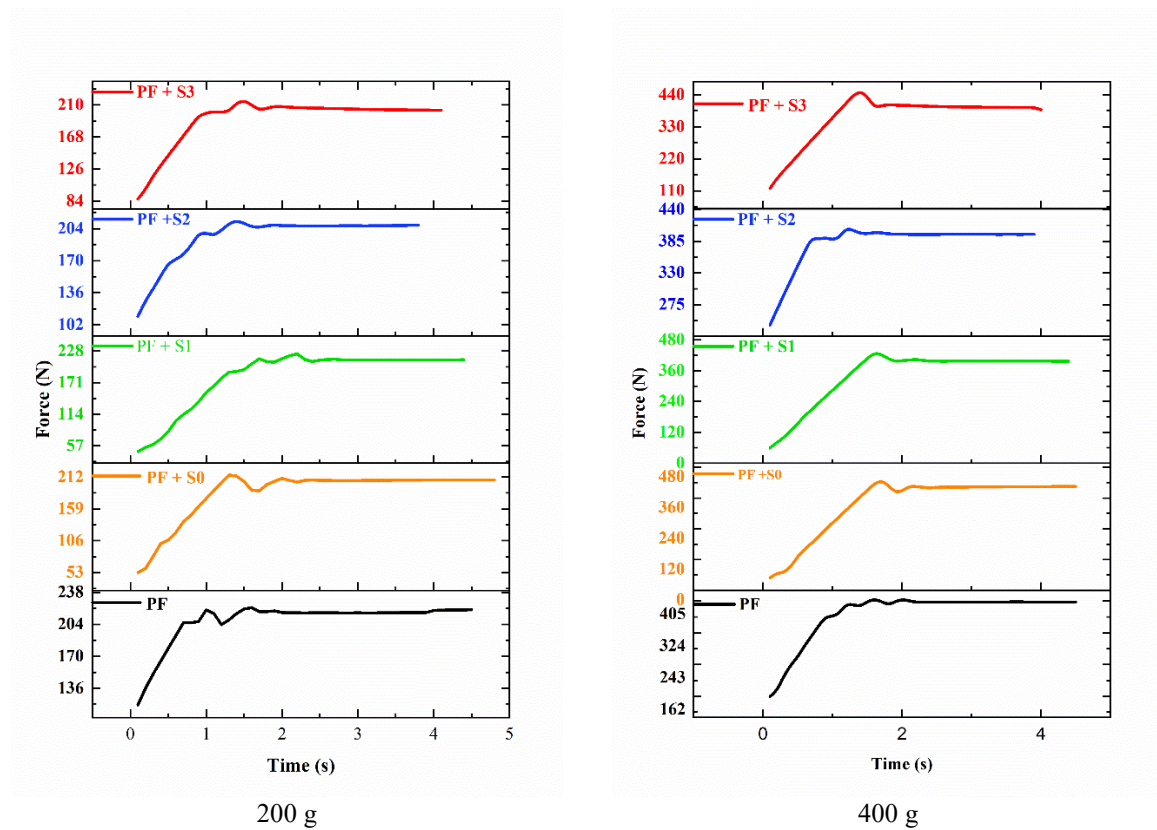
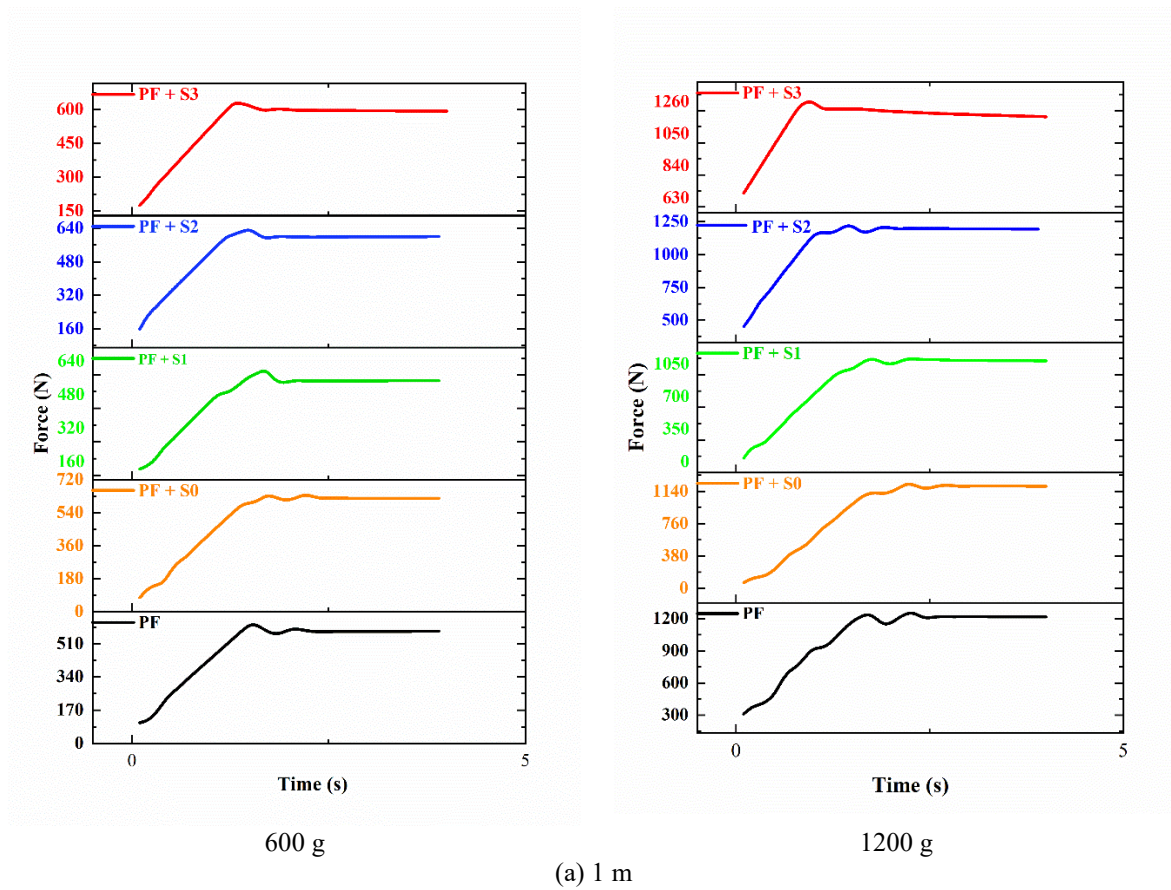
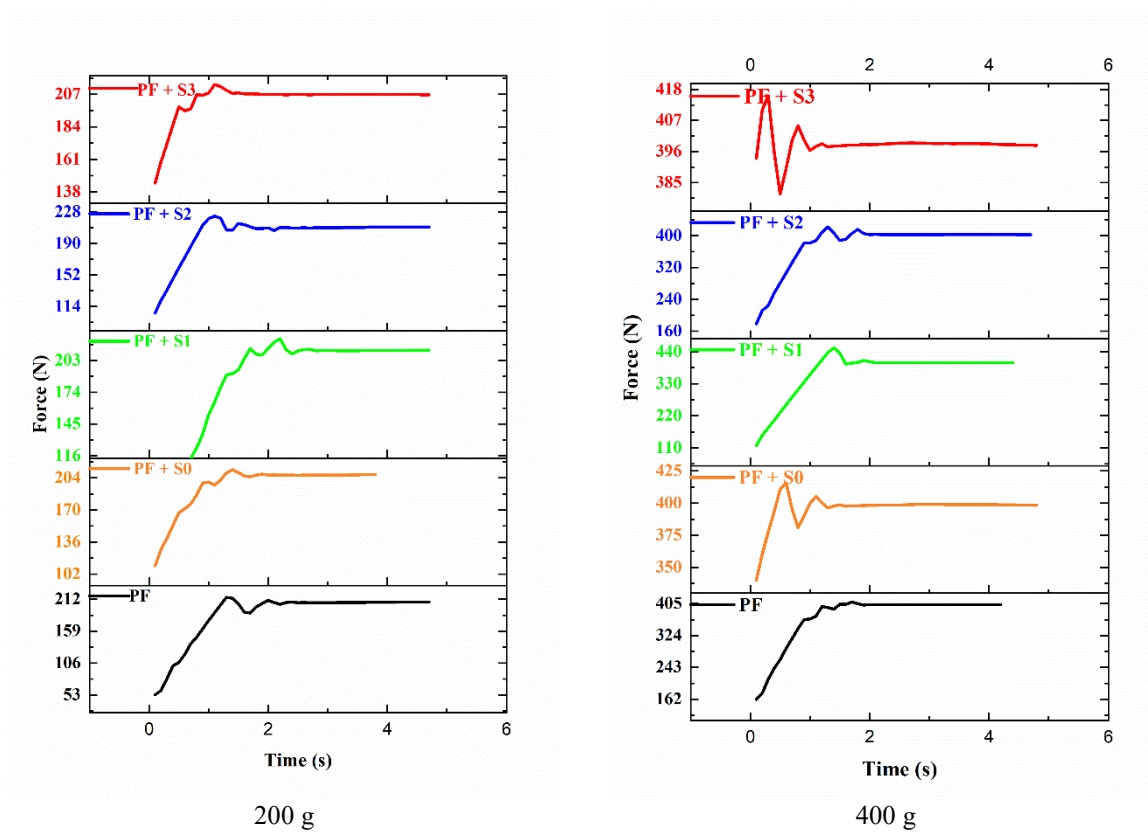


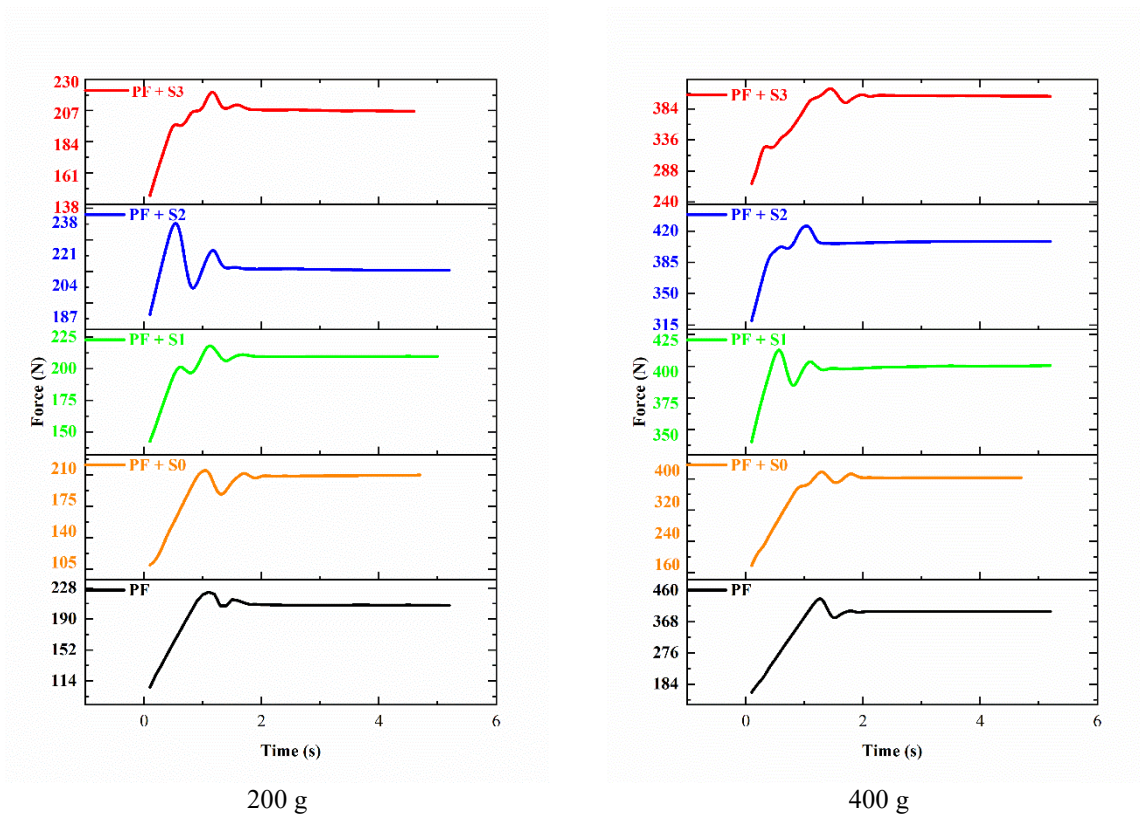
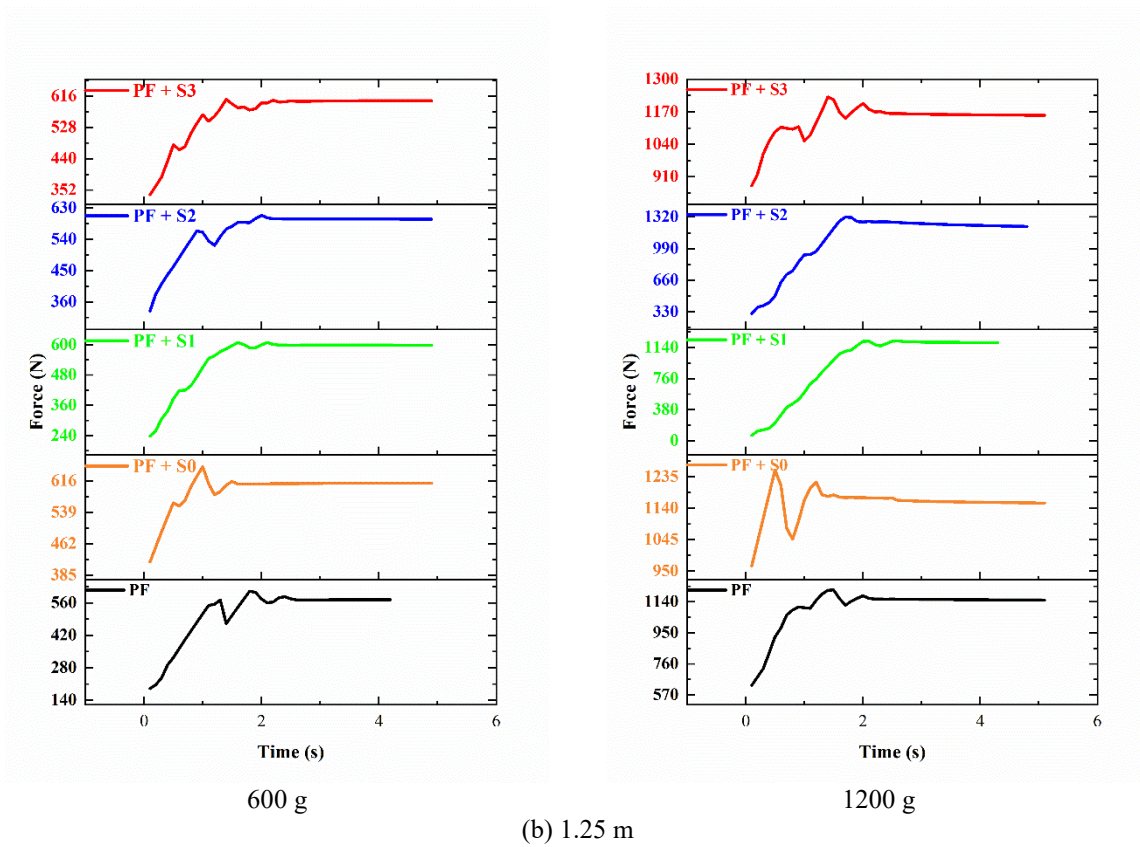
Figure 6. Drop test peak force of PF, PF+S0, PF+S1, PF+S2, and PF+S3 at drop heights of (a) 1 m, (b) 1.25 m, and (c) 1.5 m





(a) 1 m





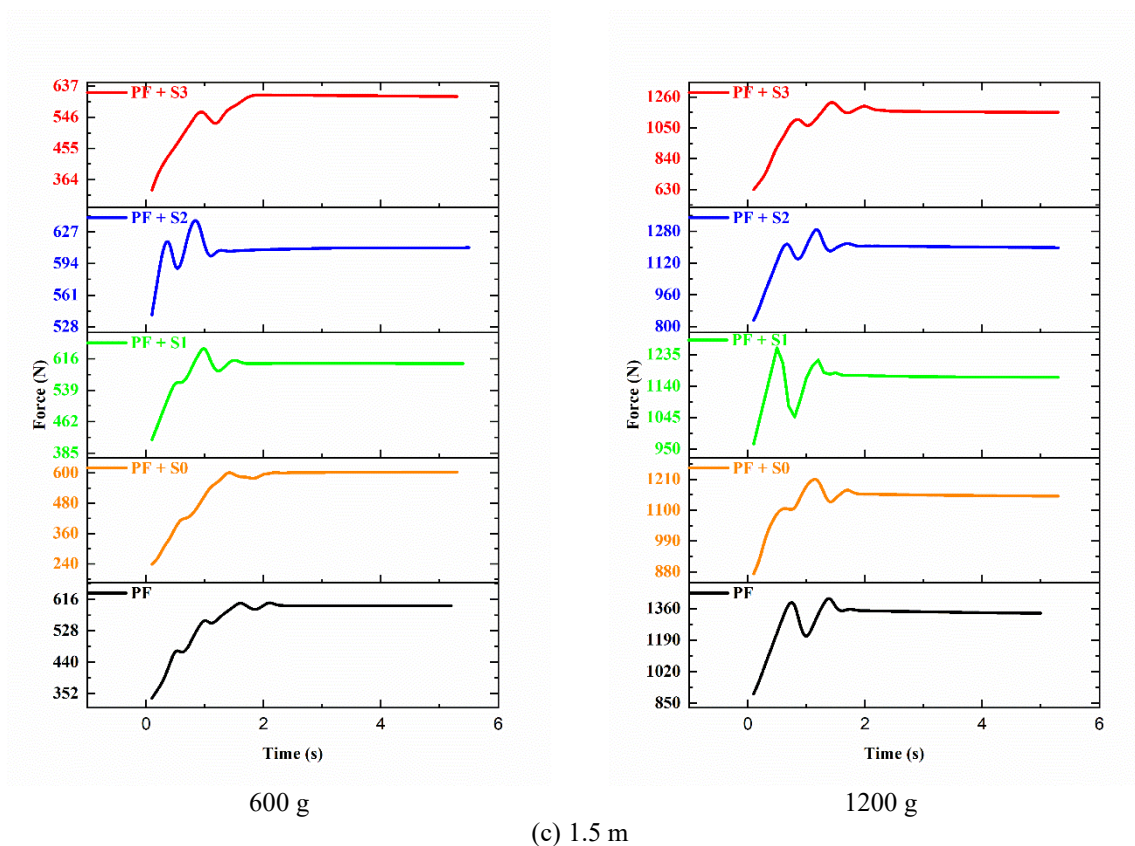


Figure 7. Force time profiles of PF, PF+S0, PF+S1, PF+S2, and PF+S3 at drop heights of (a) 1 m, (b) 1.25 m, and (c) 1.5 m

Impact Duration, Impulse, and Energy Absorption

Figure 8 shows that the impact duration increased with increasing impact mass and drop height. Among all samples, PF+S3 consistently showed the longest impact duration, especially at 1200 g and 1.5 m. This indicates that PF+S3 was able to prolong the contact time during impact, thereby reducing the severity of force transmission. In this study, a longer impact duration reflects better damping behavior rather than higher load-bearing capacity, as discussed separately in the previous sub-section on peak force and force-time response.

Figure 9 shows that the impulse trend was different from the force response. At 1.0 m, PF+S0 showed the highest impulse, around 180 N·s, indicating a long contact duration at relatively low impact severity. At 1.25 m, the impulse values dropped to about 10-35 N·s for all samples, suggesting a shorter effective contact despite the increase in impact height. At 1.5 m, the impulse increased again, and PF+S3 showed the highest value, around 90 N·s, indicating the most effective momentum absorption under the highest impact condition. This behavior occurs because impulse depends on both the magnitude of the force and the contact duration, not on peak force alone. Overall, PF+S3 showed the most favorable energy-absorption behavior under high-energy impact because it combined a longer impact duration with a higher impulse at 1.5 m. This result confirms that the superior performance of the 20–40 nm MWCNT system was governed not only by structural densification, but also by more effective STF-mediated damping, load redistribution, and adaptive shear-thickening reinforcement. Similar STF-based systems have also shown that improved damping and delayed force transmission contribute to better impact mitigation [10], [13].

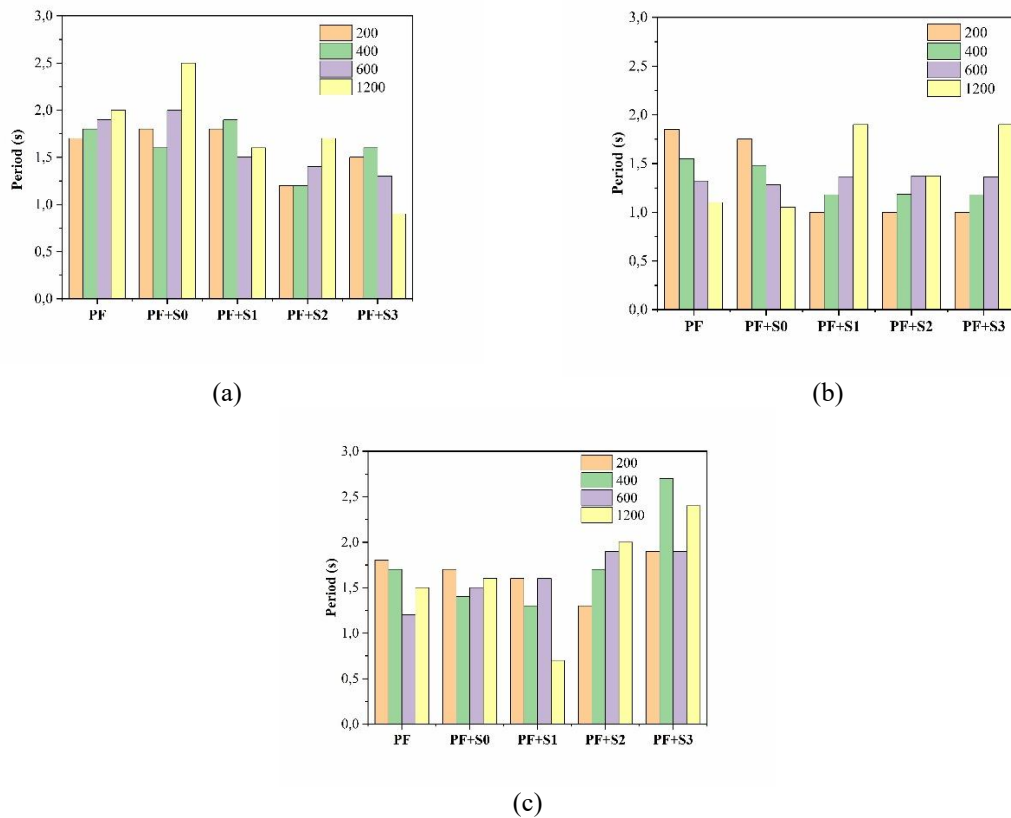


Figure 8. Drop test impact period result of PF, PF+S0, PF+S1, PF+S2, and PF+S3 at drop heights of (a) 1 m, (b) 1.25 m, and (c) 1.5 m

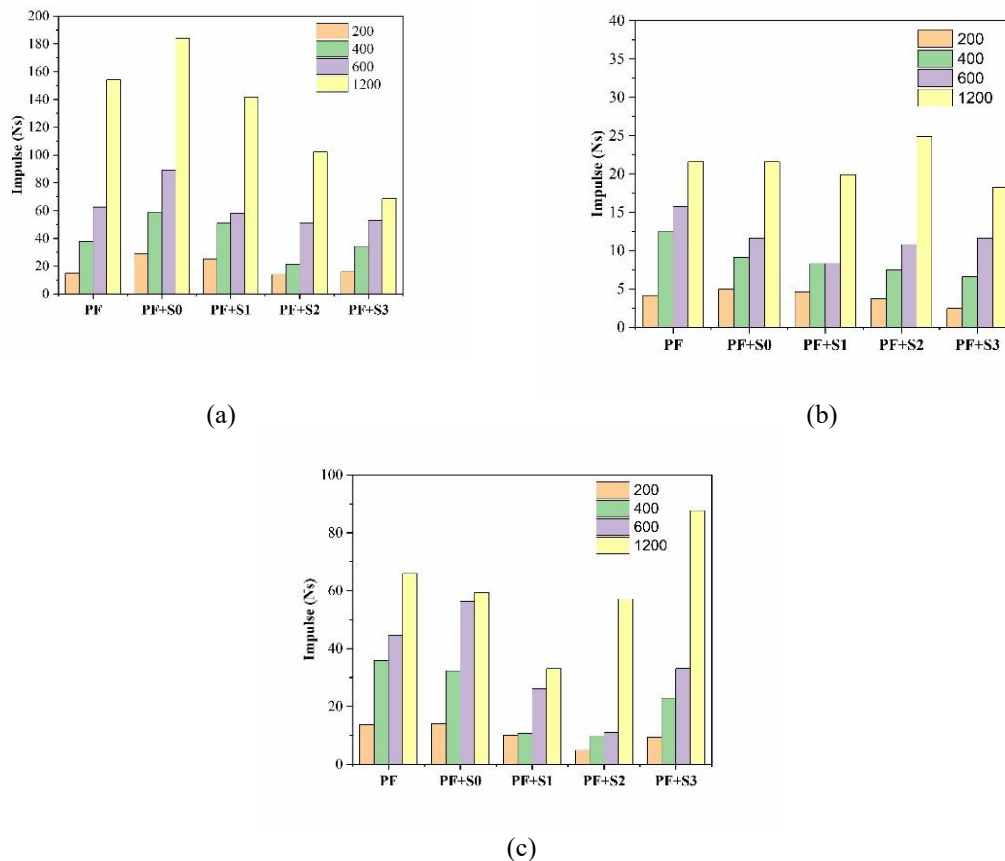


Figure 9. Drop test impulse result of PF, PF+S0, PF+S1, PF+S2, and PF+S3 at drop heights of (a) 1 m, (b) 1.25 m, and (c) 1.5 m

CONCLUSION

This study demonstrated that the adaptive impact response of polyurethane foam was significantly improved by impregnation with polyethylene glycol 400 (PEG 400)-silica (SiO₂)-based shear thickening fluid and was strongly influenced by multi-walled carbon nanotube (MWCNT) diameter. Among all formulations, PF+S3 containing 20–40 nm MWCNTs showed the best overall performance, with the most compact and homogeneous morphology after impact, the earliest thickening onset at around 100 s⁻¹, and the highest peak viscosity of approximately 220 Pa·s. Under impact loading, PF+S3 also exhibited the most stable force-time response, the longest impact duration, and the highest impulse under the highest impact condition, indicating the most effective momentum absorption and energy dissipation. Importantly, this superior response was not governed only by densification, since the densest sample was PF+S0, whereas PF+S3 provided the best morphology, rheological response, and impact behavior. These findings confirm that the geometric dimension of the nanofiller, particularly MWCNT diameter, is a critical parameter in controlling STF distribution, silica-particle connectivity, load transfer, and damping behavior within the porous foam structure. Therefore, shear thickening fluid (STF)-reinforced polyurethane foam containing 20–40 nm MWCNTs offers strong potential as a lightweight adaptive impact-mitigation material. Future work should include direct gravimetric STF uptake measurement, quantitative pore-size and cell-density analysis, repeated-impact durability evaluation, direct elastic modulus characterization, and application-oriented field validation in helmet liners and automotive energy-absorbing panels.

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