Chapter 3
Deceleration Behavior of Shear-Thickening Fluid Impregnated Foams Under Low-Velocity Impact

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3.1 Introduction

The acceleration or deceleration concept is a critical issue in many applications including sports, automotive, aerospace and military and industrial fields. In these applications, energy must be dissipated to prevent injuries or damages to the surrounding environment. Various materials and devices have been developed to avoid sudden acceleration or deceleration including foams, gels and polymers. However, these materials may not always provide sufficient protection or may be too bulky to be practical in certain applications.

Shear-thickening fluids (STFs) are a promising alternative for these kinds of applications due to their unique properties. STFs are suspensions of solid particles in an inert liquid medium that exhibits a quick increase in viscosity under high shear rates. This unique property allows STFs to dissipate energy rapidly when subjected to sudden acceleration, deceleration, impact or shock loading. The development of STFs for protective applications has gained significant attention in recent years. Researchers have explored various types of particles and liquids to fabricate STFs with optimal properties for enhanced protection. One recent development in STF is the use of additive fillers in the suspensions. Fillers are made of any kind of advanced materials with different properties such as size, shape or surface chemistry. By controlling the composition of fillers, researchers can create multi-phase STFs with

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tailored properties. In recent works [1–5], multi-phase STFs were fabricated by using various particle fillers. It was stated that rheological properties could be altered by changing the parameters related to the fillers. Moreover, multi-phase STF was also integrated into high-performance textiles to enhance the protective properties [6–8]. According to the results, fillers in STF provided an additional energy-absorbing mechanism during the impact process. STFs have been investigated for various protective applications including protective clothing, impact-resistant structures and shock-absorbing devices. These smart materials have been used to create protective clothing that can attenuate impact energy. A recent study conducted by Bajya et al. [9] demonstrated that STF-impregnated fabrics could provide superior protection against ballistic impact compared to conventional fabrics. STFs have also been used to create impact-resistant materials such as composites and coatings. Sun et al. [10] demonstrated that STF-impregnated carbon fiber–reinforced composites exhibited superior impact resistance in comparison to conventional composites. STF was also used as a filler in sandwich structures to enhance the impact resistance [11–13]. Based on the results, promising achievements were made to design anti-impact systems. In another study [14], polyester foams were impregnated with STF, and a multilayered composite was fabricated with foams and warp-knitted spacer fabrics. According to the impact test results, STF integration into the composites greatly helped in enhancing energy-absorbing capacities. Shock-absorbing devices such as helmet liners and vehicle bumpers have also benefitted from the protective performance of STFs. Serra et al. [15] showed that STF-filled helmets provided superior protection against impact compared to conventional helmets. In another work [16], cork layers were intercalated with STF to enhance the shock-absorbing capabilities for crashworthiness applications. STF inclusion provides significant reduction in peak forces to prove its protective performance. Another concept related to protection is deceleration behavior that is of importance for many engineering applications. Deceleration concept is about protecting humans or devices from sudden g-forces in case of impacts or crashes. For this purpose, various protective designs have been developed in recent years. Sheikhi et al. [17] developed a protective design by including STF in cork panels for sensitive systems such as electronic devices, robotic structures and unmanned aerial vehicles to avoid sudden acceleration or decelerations.

In this study, STF-impregnated polyurethane foams are used for a smooth deceleration process under impact, crash or sudden braking conditions. Two different STF formulations are used in the impregnation stage. The first STF is based on silica and polyethylene glycol, which is known as a single-phase STF. On the other hand, the second one includes carbon nanotube (CNT) fillers in the single-phase STF called the multi-phase STF. The composites are tested in a drop tower system by placing them under a dropping mass. An accelerometer is attached to the dropping mass, and the deceleration of the dropping mass is recorded during the impact process. According to the results, STF impregnation provides significant reduction in the peak deceleration values in the foams. CNT fillers lead to a further performance improvement in the deceleration behavior.

3.2 Experimental Details

The single-phase STF used in this study was based on a 20-nm-fumed silica (from Evonik) and 400-g/mol polyethylene glycol (from Sigma-Aldrich). In the fabrication process, silica was gradually added in the polyethylene glycol pool and distributed by a high-speed homogenizer for 1 h. An excessive amount of ethanol was used to facilitate the blending process. After completing the homogenization, the suspension was rested to remove the ethanol from the mixture. The silica concentration was 60 wt% in the final single-phase STF. An 8–10-nm CNT (from Nanografi) was included in the single-phase STF to produce the multi-phase STF. The CNT amount was kept at 1 wt% in the suspension. Polyurethane foams (from Espol) were sized into 40 mm × 40 mm × 40 mm before STF impregnation. Then, the foams were immersed into an ethanol-diluted STF pool. Upon ensuring that the foams were fully impregnated with the suspension, they were rested for 3 days to remove the ethanol from the structures. Figure 3.1 shows the specimen photos. Table 3.1 gives the specimen details in this study.

As suggested in an earlier study [18], a drop tower system was used in the deceleration tests as shown in Fig. 3.2. A 15-mm diameter hemispherical impact head was loaded with 1 kg, and it was dropped from three different heights: 50, 100 and 150 mm. Deceleration of the dropping head was collected by an accelerometer attached on the head.

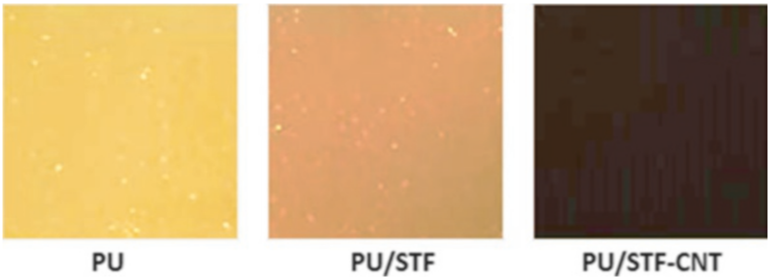

Fig. 3.1 Specimens before and after STF treatments

Table 3.1 Specimens in the deceleration tests

Specimen	Content
PU	Pristine polyurethane foam
PU/STF	Single-phase STF-impregnated polyurethane foam
PU/STF-CNT	Multi-phase STF-impregnated polyurethane foam

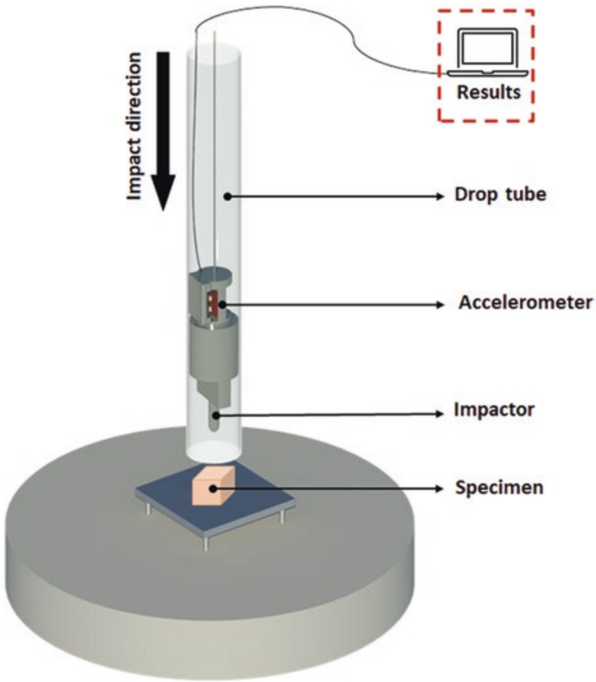

Fig. 3.2 Drop tower system in deceleration testing

3.3 Results and Discussion

Figure 3.3 shows the deceleration curves for the specimens subjected to drop tests from 50 mm. From these charts, peak deceleration values for the specimens PU, PU/STF and PU/STF-CNT are 77.8, 37.4 and 22.2 g, respectively. It is clear that there is a decreasing trend in the peak decelerations by treating the polyurethane foam with single-phase and multi-phase STFs. Single-phase STF leads to the peak value that is almost half of that by the pristine polyurethane foam. Moreover, multi-phase STF provides a further decrease in the peak deceleration, thereby producing about one-third of that obtained by the pristine polyurethane foam. The reductions in the peak values are significant due to the effect of STF impregnation. Another important point is about the time interval of the loadings on the dropping mass. As shown in the graphs, the dropping mass is loaded in a very short time period upon impacting the pristine polyurethane foam, which produces a drastically sharp deceleration. On the other hand, the time spans during the dropping mass loading are extended by using single-phase and multi-phase STFs in the polyurethane foams. Comparing the single-phase and multi-phase STF-impregnated cases, it is obvious that multi-phase STF provides an extended impact loading on the dropping mass. From these findings, it is possible to state that STF impregnation especially the multi-phase one leads to a smoother deceleration on the dropping mass in

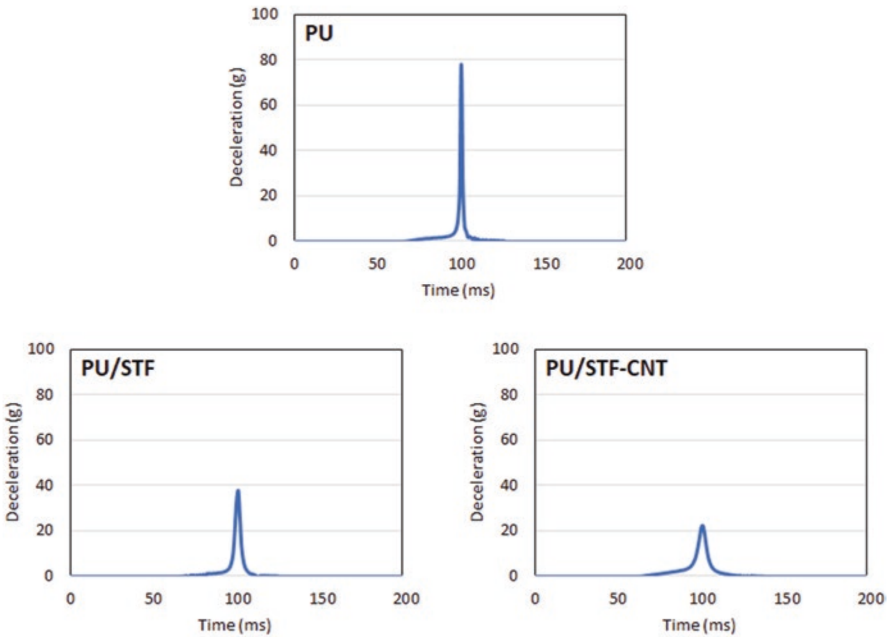

Fig. 3.3 Deceleration curves for the specimens

comparison to the pristine polyurethane foam. Hence, the detrimental effect of deceleration is lowered by the contribution of STF impregnation in the polyurethane foam [19–21]. The extended time period during the loading process in the STF cases can be associated with the shear-thickening behavior. When the STF is introduced to a sudden loading, shear-thickening mechanism is triggered, thereby increasing the suspension viscosity [22]. The suspension behaves stiffer due to this quick change in the viscosity. Since the polyurethane foam is impregnated with this fluid, the viscosity increase is spread from the impact point to the far fields over the foam. For this reason, the polyurethane foam exhibits stiffer characteristics during the loading process. The rheological phenomenon in the STF provides an enhanced dissipation characteristic for the polyurethane foams impregnated with this smart fluid. Because the STF acts as a continuous matrix in the polyurethane foam, thickening behavior predominates over the whole structure beginning from the impact point. Thus, stiffened matrix within the polyurethane foam leads to a whole-body response to the loading instead of a local response at the impact point. For this reason, loading process is delayed over an extended time period while suppressing the sharp increase in deceleration. Regarding the multi-phase STF, it is possible to mention that CNT fillerscontribute to this process consequently providing more extended time span as well as having suppressed deceleration. Due to the advanced strength of CNT fillers, the texture in the multi-phase STF gets much stiffer during shear thickening. Furthermore, CNT fillers increase the solid particle amount in the suspension, thereby leading to an increase in the overall viscosity profile. This is also associated with the enhanced stiffness in the system.

Figure 3.4 shows the peak decelerations on the dropping mass for different drop heights. As shown in the chart, peak values of the deceleration increase by increasing the drop height. On the other hand, STF impregnation provides a lowering effect in the peak decelerations for each drop height. Although single-phase STF is significant in lowering the peak decelerations, multi-phase STF provides an increased performance in this process. Table 3.2 shows the reductions in the peak deceleration by the single-phase and multi-phase STFs with respect to the pristine polyurethane foam. From the results, STF effect diminishes in intensity by increasing the drop height. This can be associated with the increasing impact velocity that produces higher shear rates in the specimens. In previous works [23–26], it is stated that the STF effect is pronounced at low-velocity impact conditions rather than the higher velocities. The solid particles in STF establish a chain-like force networks during the shear-thickening process. These particle networks bear the developed forces during thickening phenomenon in the suspension. However, the particle clusters cannot keep their integrity at higher shear rates, and therefore, a microstructural breakdown is observed in the particle networks. For this reason, shear thickening is suggested for low-velocity impact conditions for an enhanced protective performance. Otherwise, STF performance gradually reduces as shear rate increases. From this fact, our results show a good match with the literature. It can also be mentioned that the developed stresses show a reduction after the maximum viscosity point in the suspensions, thereby leading to a lower stress-bearing capacity beyond this point. For this reason, shear rates during the impact process should be in the vicinity of that point to have the maximum viscosity jump, thereby properly

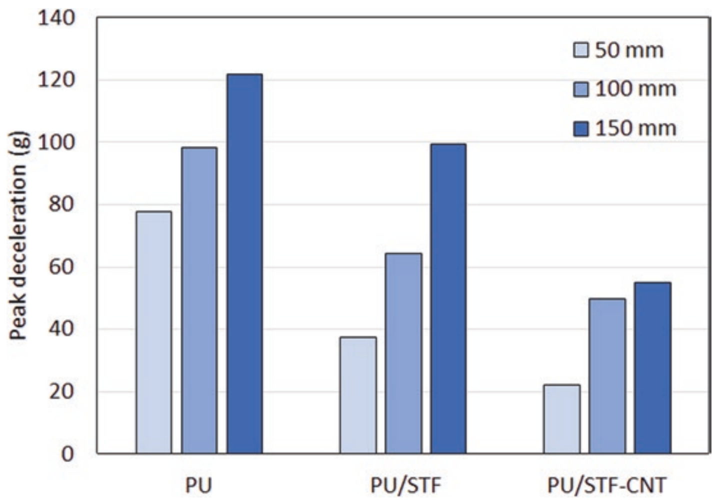

Fig. 3.4 Peak decelerations for the specimens

Table 3.2 Reductions in peak deceleration with respect to pristine polyurethane foam

	Drop heights		
Specimen	50 mm	100 mm	150 mm
PU/STF	52%	35%	18%
PU/STF-CNT	71%	49%	55%

benefitting from the shear-thickening behavior. According to previous studies [27–31], shear rates in the range of 100–500 s^{-1} generally correspond to the maximum viscosity points for the STFs based on silica and polyethylene glycol.

3.4 Conclusions

STFs are a promising alternative for protective applications due to their unique properties. Recent developments in STFs such as multi-phase systems have expanded their potential application in suppressing deceleration. STFs have been explored for various protective applications including protective textiles, impact-resistant structures and shock absorbing systems. While the development of STFs for protective applications is still in its early stages, the potential benefits are significant. STFs have a great potential to provide lightweight solutions in protective systems especially for low-velocity conditions. However, there are still challenges to be addressed such as tailoring the microstructural properties, controlling the rheology and preventing the degradation under various ambient exposures. Deceleration concept is one of the promising fields for STFs. Sensitive devices such as electronic units, robotic structures and unmanned aerial vehicles as well as humans suffer from sudden acceleration or deceleration in many different conditions such as crashworthiness applications and sharp maneuvers. In this study, a silica and polyethylene glycol–based STF was used as an impregnation agent for polyurethane foams. Moreover, the STF was filled with 1 wt% of CNT fillers to have a multi-phase system. The deceleration behavior of polyurethane foams was tested in a drop tower setup. An accelerometer was attached to a dropping mass, which was dropped on the polyurethane foam specimens from three different heights. Deceleration curves of the dropping mass were obtained during the impact processes, and therefore, the STF effect was discussed. According to the results, STF impregnation provides a significant reduction in the peak deceleration compared to the pristine polyurethane foam. Moreover, CNT inclusion in the STF led to an additional performance increase by further lowering the peak decelerations. Although the STF treatments provide a considerable reduction in the peak decelerations, shear-thickening effect had a loss of performance at high-velocity conditions. STF-impregnated polyurethane foams are promising structures in protective applications; however, the rheological properties of STF and the structural design of the foams have to be precisely tailored to take advantage of smart behavior in these systems.

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