ORIGINAL ARTICLE

Deceleration behavior of multi-layer cork composites intercalated with a non-Newtonian material

Mohammad Rauf Sheikhi[1,2] · Selim Gürgen[3]

Abstract

Impact or sudden accelerations are strictly avoided by sensitive systems such as electronic devices, robotic structures and unmanned aerial vehicles (UAVs). In order to protect these systems, various composites have been developed in recent years. Due to its excellent energy absorbing capabilities as well as eco-friendly and sustainable properties, cork is one of promising materials dedicated to protective applications. In this study, we benefit from cork agglomerates in multi-layer design considering its advantages such as high flexural stiffnesstoweight ratio and good buckling resistance over monolithic structures. In addition, a non-Newtonian material, namely shear thickening fluid (STF) was incorporated in this design. STF shows rapid increase in its viscosity under loading and thereby enabling a stiffer texture that contributes to protective performance. At rest state, STF exhibit fluidic behavior and provides flexibility for composite. In the experimental stage, deceleration behavior of these composites was investigated. According to the analyses, STF exhibits promising results to lower peak decelerations while extending time period of deceleration under impact loading. STF contribution is pronounced by using this material in a closed medium such as in wrapped foam to avoid spilling out of composite during impact. The designed eco-friendly smart composites are suggested to cover internal parts in sensitive systems. Micro-mobility helmet is another prospective application area for cork/STF structures since they provide light-weight, excellent flexibility and good deceleration behavior.

Keywords Deceleration · Multi-layer composites · Cork agglomerate · Shear thickening fluid

1 Introduction

When it comes to protecting delicate core components as such in electronic devices, robotic systems and unmanned aerial vehicles (UAVs) from external impact loads or sudden accelerations, high-quality protective solutions are crucial [1]. This is also valid for safety of human in traffic since micro-mobility vehicles have been rapidly increased in recent years. Over the last two decades, researchers have made great efforts to increase protection while taking ease-of-use into consideration. At this point, weight and flexibility come to the fore to design an efficient protective structure. Cellular materials rise to the occasion in protective systems due to their excellent energy absorbing properties, high stiffness-to-weight ratio and lower density as well as other benefits such as good thermal and acoustic insulation [2] and vibration damping capabilities [3]. Cork, as a natural cellular material, has been adapted to different kinds of protective applications. In addition to typical advantages of cellular materials, cork has environmentally friendly properties that provide sustainable applications. Cork is made from the outer bark of an oak tree, botanically known as *Quercus suber* L. [4]. The outer bark can be peeled and removed multiple times over its lifetime without severe damage to the tree. Since the cork oak can live up to 200 years, this constitutes a steady source of renewable and reusable raw material while offering a unique look and touch, which makes it difficult to be replaced by synthetic materials [5]. Moreover, easy of manufacture results in a very low carbon footprint and makes it an appealing "green" material. Reusability of

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cork is another attractive factor in terms of sustainable applications. The mechanical reaction of cork is extremely sensitive to loading medium and rate. This material has a unique combination of properties that make it ideal for a variety of applications apart from protection. Some prominent properties of cork are low density, excellent thermal and acoustic insulation, impermeability to liquids and gases, high coefficient of friction, good resilience, near-zero Poisson's ratio and imperishability [6].

Fernandes et al. [7] reported the reliability of replacing synthetic foams with an agglomerated cork for impact energy absorbers. Their results and comparisons show that it appears to be a completely plausible solution for multiple impact applications. Jardin et al. [8] prepared cork layers made from different size of cork granules. They tested these layers under dynamic loading and stated that shock response of cork layers is heavily depended on granule size and layer density. In the light of these results, optimization of cork layers was studied in previous works [9]. Granule size and density as well as other variables such as binding agent and its amount were tailored for enhanced mechanical properties. To understand the reliability of cork, anti-impact behavior of cork agglomerates was also tested in various environmental conditions. Kaczynski et al. [10] studied the impact response of cork agglomerates by chancing the ambient temperature from − 30 to 100 °C. From the results, energy absorbing capability is affected by temperature especially at lower and upper levels. Mechanical response of cork under humidity was studied by Lagorce-Tachon et al. [11]. According to their work, hydration affects cork modulus by lowering the rigidity. Despite its impermeable structure to liquids and gases, formation of water clusters on polymeric binder deteriorates the properties in cork agglomerates consisting of cork granules and polymer binder. Cork was subjected to aggressive impact conditions such as reaching impact energies up to 850 J in a previous study [12]. Based on the results, cork keeps structural integrity up to the impact levels of 250 J by showing a full recovering behavior despite a compression rate of 80%. It still provides a survivable chance above 250 J however, crack formations are visible in the specimens while lacking recoverability to initial shape. In an another study [13], cork liners were designed for a helmet application being proposed to motorcyclists. In the light of test results, cork is suggested as an alternative to expanded polystyrene foams. Similar to motorcyclists, micro-mobility users benefit from cork based helmets in head protection [14]. Cork is also studied in various composite designs to enhance the energy absorbing capability. Fernandes et al. [15] produced natural flax fiber based laminates to cover a cork layer in multi-layer composites. A bio-resin matrix was used as a binder in this eco-friendly design. They stated that mechanical properties and anti-impact behavior are competitive to fiberglass and epoxy based composites. In addition to natural reinforcing components, advanced fillers such as carbon fibers were also brought together with cork to produce stiffer composites.

In other respects, there have been notable improvements in protective systems by using a non-Newtonian smart fluid, so-called shear thickening fluid (STF), which increases its viscosity under loading [16]. In recent years, STF has been used as an impregnating agent in textile based protective structures [17]. Previous studies [18] reported that STF in yarn gaps within textiles exhibits a sudden viscosity increase upon impact and thus, a stiffer texture is introduced in the structure. For this reason, friction in the structure is increased by the increasing yarn coupling [19]. Consequently, energy absorbing capacity of textile is improved by the contribution of STF impregnation [20]. In addition to textile structures, STF has been used in bulk form in some recent works [21]. According to these studies, shear thickening rheology has a promising potential in protective composites. However, a good effort is required to design efficient composite structures to benefit from STF rheology against impacting threats. To do so, a multi-layer system is design due to its excellent performance under impact conditions. Multi-layer structures have significantly high flexural stiffnesstoweight ratios in comparison to monolithic systems [22]. Moreover, multi-layer designs provide higher buckling resistance and lower lateral deformations for impacted structures. With a proper material selection, structural weight is generally reduced in multi-layer designs while not compromising flexibility compared to monolithic ones. In the light of this, we made an effort to design eco-friendly multi-layer cork composites enhanced by STF intercalation. To integrate STF into multi-layer configurations, polyester foam layers were filled with this smart fluid. Because polyester foam is a low-density material, it provides a lightweight structure as well as containing the STF in the composites. Deceleration behavior of these composites was investigated. According to the analyses, STF exhibits promising results to lower peak decelerations while extending time period of deceleration under impact loading. STF contribution is pronounced by using this material in a closed medium such as in wrapped foam to avoid spilling out of composite during impact. The designed eco-friendly smart composites in this work are suggested to cover delicate internal components mainly in UAV, robotic and electronic applications subjected to foreign object damage or sudden accelerations. In addition to these systems, micro-mobility helmets are prospective application areas for cork/STF structures since they provide light-weight, excellent flexibility and good deceleration behavior.

2 Experimental details

2.1 Manufacturing of multi-layer composites

STF was synthesized by mixing 20 nm silica particles (from Evonik) in a polyethylene glycol (PEG) medium having a molar mass of 200 g/mol (from Sigma-Aldrich). Mixing procedure was carried out for the suspension with silica loading of 20 wt% by using a high speed homogenizer. The mixture was rested for 1 day to remove air bubbles.

Multi-layer structures were produced from cork agglomerates supplied from Ducork Inc. Cork exhibits excellent energy absorbing behavior while providing eco-friendly and sustainable properties for green applications. Foam layers from Orsa Inc. were used to contain STF in their porous structures and thereby including this non-Newtonian material in multi-layer composites. Table 1 gives the details of cork and foam layers.

In the composite designs, components were sized into 80 mm × 80 mm and stacked up in multi-layer assemblies. Foam layers were used in three different forms such as neat, STF filled, and STF filled and wrapped. In the neat form, as-received foams were used in the specimen preparations. In the STF filled form, foam layers were immersed in an STF pool diluted by ethanol at 1:3 volumetric ratio and rested to remove the ethanol from the foams. In the STF filled and wrapped form, STF filled foams were covered with one layer of stretch film. Figure 1 shows the components in multi-layer composites. Figure 2 shows the multi-layer configurations used in this work.

2.2 Rheological measurements

Non-Newtonian rheology of STF was investigated in an MCR 301 Anton Paar rheometer by using parallel plate configuration. STF was sheared from 0 to 1000 s^{-1} shear rate while the gap size between the plates was kept at 0.20 mm during the tests. A preshear of 1 s^{-1} was applied
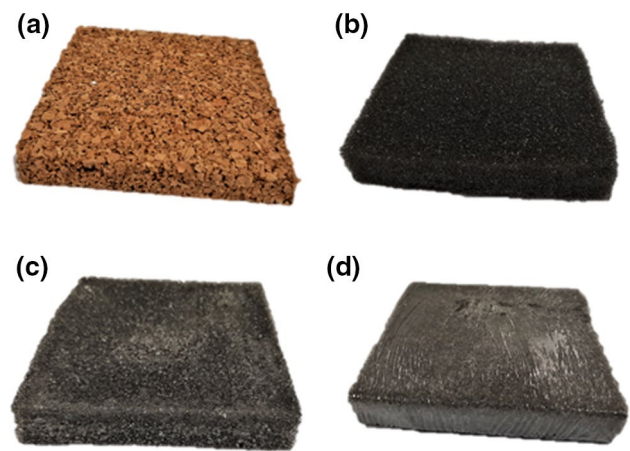

Fig. 1 **a** Cork agglomerate, **b** neat foam, **c** STF filled foam and **d** STF filled and wrapped foam

to the samples for 60 s prior to tests to remove the loading effects.
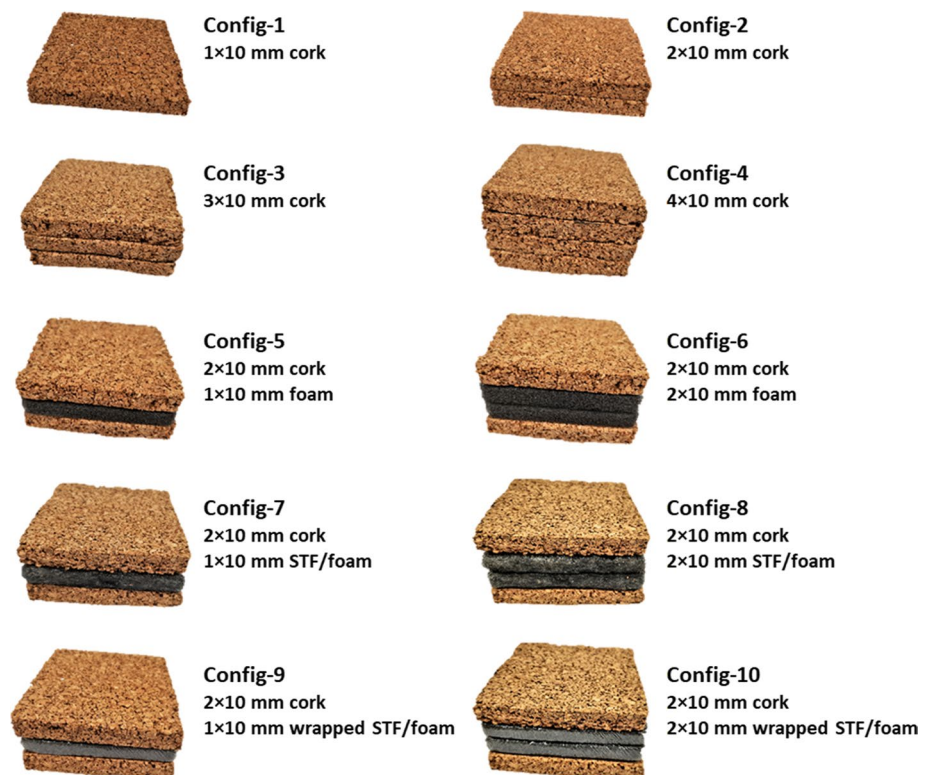
2.3 Deceleration tests

Deceleration properties of multi-layer composites were investigated in a drop tower system by falling a mass on the specimens. The falling head was a hemi-spherical rod having 15 mm diameter. The mass of the falling head was 1.10 kg, which produces impact energies of 5.40, 10.79 and 16.18 J for the drop heights of 0.5, 1.0 and 1.5 m respectively. An accelerometer bonded on the falling mass was used to measure the decelerations during the drops on the multi-layer composites. Figure 3 shows the experimental setup for deceleration tests.

3 Results and discussion

3.1 STF rheology

Figure 4 shows the flow curves of PEG and STF in terms of viscosity and shear stress. As shown in Fig. 4a, PEG, carrier liquid of STF, has a constant viscosity under increasing shear rate. However, Newtonian behavior of PEG turns into non-Newtonian characteristics by adding silica particles in the base liquid. Clearly seen that silica inclusion increases the initial viscosity of the base liquid due to enhanced density. Moreover, inter-particle adhesion gets stronger as silica additives increase in the medium [23]. For this reason, suspension viscosity shows an upper shift at zero shear rate. Another change in the flow characteristics is thickening phenomenon that is observed as a drastic jump in viscosity beyond a critical point. This behavior stems from hydrodynamic interactions at moderate shear

Table 1 Details of the components

Cork layers	
Density	240 kg/m³
Granule size	3.5–5.0 mm
Thickness	10 and 20 mm
Foam layers	
Material	Polyester
Density	20 kg/m³
Thickness	10 mm

Fig. 2 Multi-layer composite configurations

Config-1
1×10 mm cork

Config-2
2×10 mm cork

Config-3
3×10 mm cork

Config-4
4×10 mm cork

Config-5
2×10 mm cork
1×10 mm foam

Config-6
2×10 mm cork
2×10 mm foam

Config-7
2×10 mm cork
1×10 mm STF/foam

Config-8
2×10 mm cork
2×10 mm STF/foam

Config-9
2×10 mm cork
1×10 mm wrapped STF/foam

Config-10
2×10 mm cork
2×10 mm wrapped STF/foam

Accelerometer

Falling mass

Impact head

Drop tube

Specimen

Fig. 3 Experimental setup for deceleration tests

rates. By increasing shear rate in the medium, hydrodynamic forces acting on silica particles grow stronger and thereby collecting large groups of particles together by overcoming repulsive forces between the particles. These particle groups, namely hydro-clusters hinder the liquid to flow by acting as obstacles in the flowing zone [24]. For this reason, the suspension introduces to a shear jamming that results in a viscosity increase in the system [25]. As shear rate reaches upper levels, inter-particle distances become far smaller to such scales that physical contacts take place between the particles. This contacted microstructure generates stress networks in the suspension, which bear the developed stresses during shear thickening process [26]. As shown in Fig. 4b, shear stress in PEG, a Newtonian fluid, is directly proportional to shear rate. However, there is a non-linear relationship in STF due to shear thickening behavior. The contacted particles in the mixture are able to withstand the developed stresses up to the peak viscosity point. Beyond this point, excessive loadings lead to a structural breakdown in the particle networks and consequently, suspension shows a reduction in viscosity [27]. At the peak viscosity, stress chains extend as much as possible. This extension process constitutes the basis of shear thickening phenomenon just after hydrodynamic effects at moderate shear rates. According to early works [28], hydrodynamic interactions are only responsible to initiation of shear thickening mechanism that produces mild viscosity jump. However, shear thickening gets stronger and eventually, reaching to the maximum levels by the effect of particle contacts elongating to far-fields in the liquid medium.

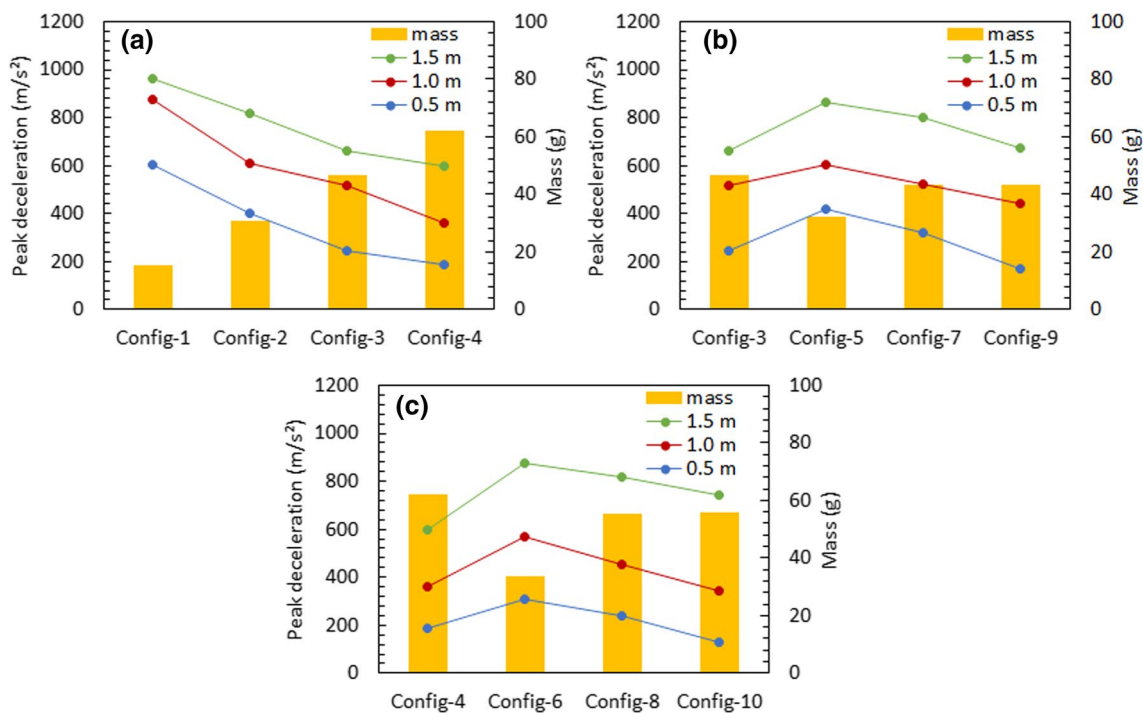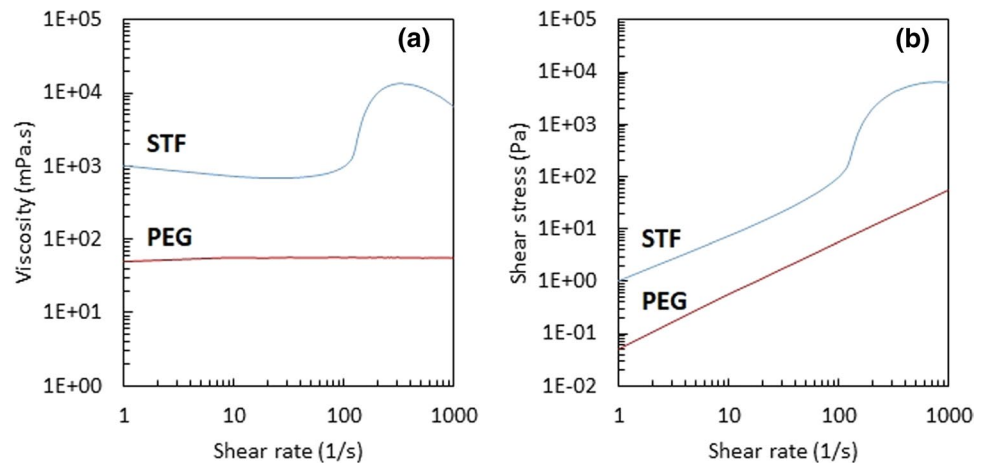**Fig. 4** **a** Viscosity and **b** shear stress curves for PEG and STF

Fig. 5 Peak decelerations for **a** cork layers, **b** three-layer composites and **c** four-layer composites

3.2 Deceleration behavior of multi-layer composites

One of the most important factors in safety applications is peak deceleration that is desired to be as low as possible [29]. Figure 5 shows the peak decelerations for different categories of specimens. As shown in Fig. 5a, number of cork layers is determinant on peak decelerations. By adding more cork layers in composites, peak deceleration is lowered significantly due to mass gain. Comparing one-layer (Config-1) and four-layer (Config-4) composites, reductions in peak deceleration are 69%, 59% and 38% for drop heights of 0.5, 1.0 and 1.5 m respectively. Despite a decreasing trend in deceleration for each drop height, cork layers are more effective in low velocities and accordingly, low energy drops. Considering three-layer and four-layer composites in Fig. 5b, c, there is a jump in peak decelerations by replacing core cork layers with neat foams (Config-3 to Config-5 for three-layer and Config-4 to Config-6 for four-layer). Similar to cellular microstructure of cork, foam layers exhibit buckling of cell walls under impact and release the absorbed energy due to its great recoverability. Although this mechanism, namely spring effect, is valid for both cork agglomerates and foam layers, polyester foam is significantly lighter than cork,

where density ratio is 1:12. Despite this lack, STF filling in porous microstructure of foams enhances the deceleration performance of composites. STF in foam layers acts as a continuous matrix. When the structure is impacted, STF shows a drastic increase in viscosity and the impact energy is distributed radially to far-fields by extending hydro-clusters from the impact point. For this reason, STF inclusion provides a stiffer behavior for the foam layers under impact. Figure 6 shows the microstructural views of cork, foam and STF/foam.

Shear thickening mechanism is retarded in STF/foam layers because of excessive STF spill out from foam layers at impact moment. This problem is overcome by wrapping STF/foam layers as such in Config-9 and Config-10. Due to the stretch film enveloping STF medium, STF pressure is increased during impact process and therefore, suspension is subjected to higher stresses that correspond to higher viscosity jumps [30]. For this reason, shear thickening behavior is effectively benefitted by the multi-layer composites. This effect is clearly observed in the peak deceleration results for drop heights of 0.5 and 1.0 m by comparing wrapped STF/foam configurations to neat cork agglomerates (Fig. 5b, c). However, wrapped design falls behind the neat cork layers for drop height of 1.5 m, which is a relatively aggressive condition corresponding to an impact energy of 16.18 J and impact velocity of 5.42 m/s. At this level, shear thickening behavior remains weak to largely absorb the impact loading. Despite this deficiency comparing to neat cork layers, shear thickening effect is obviously realized in composite

deformations as shown in Fig. 7. In the composites including neat foam and STF/foam layers, top cork layers show plugging type perforation due to relatively soft backing layers. However, radial fracture predominates top cork layer by using wrapped STF/foam layers in the composite. Because the boundaries are closed in the wrapped STF/foam layers, the suspension is confined to a closed space and thereby introducing a high level pressure jump upon loading. For this reason, hydro-clustering extends from impact point to far-fields and therefore, shear thickening process takes place in the whole foam layer. As a result, this layer provides a stiffer backing fill for the above cork layer and consequently, the impact force is radially distributed rather than accumulating on the impact point. During this process, top cork layer is broken into pieces due to polyurethane matrix cracking. In addition, cork granules and foam at the impact point exhibit permanent deformation despite their great recoverability behavior. Figure 8 shows cell crushing in the microstructures of cork agglomerates and foam after impact. In the wrapped STF/foam configuration, shear thickening contribution is much more pronounced and by this means, the composites show an integral response instead of local concentrated one. Deceleration performance of composites is greatly enhanced by this change.

Recalling Fig. 5, mass efficiency of the multi-layer composites can be discussed. Obviously, there is a linear increase in target mass by adding more cork layers. As shown in Fig. 5a, mass increase yields a clear reduction in peak decelerations. However, the relationship between

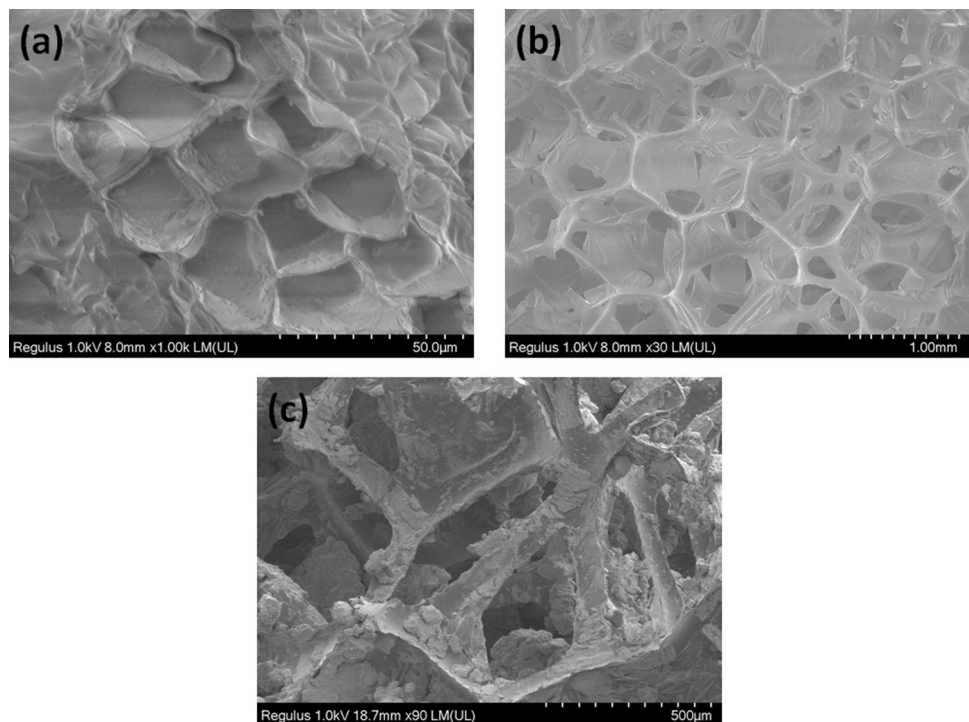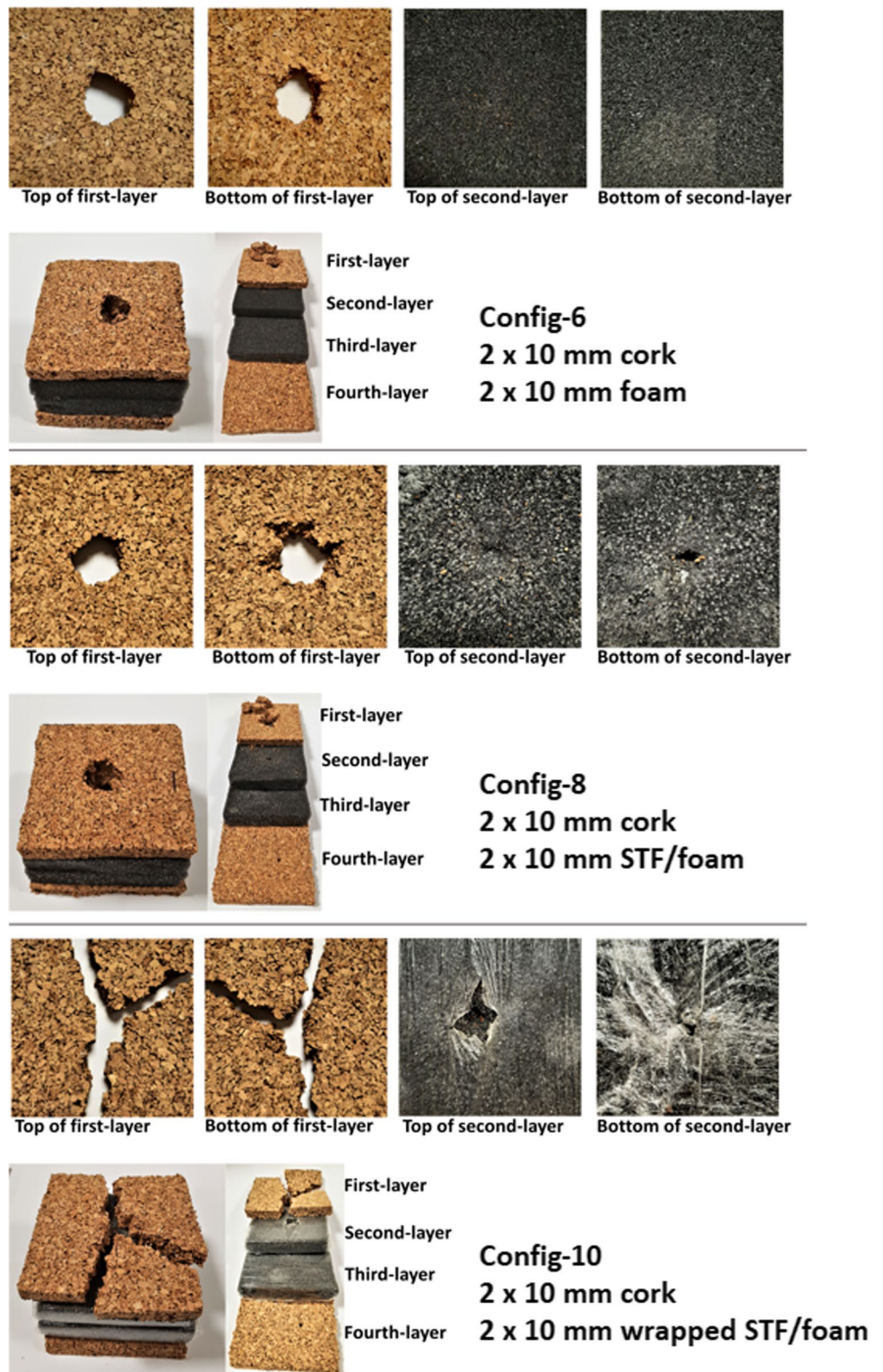**Fig. 6** Microstructural view of **a** cork, **b** foam and **c** STF/foam

Fig. 7 Deformations on multi-layer composites after 1.5 m drops

target mass and peak deceleration is complicated for the configurations given in Fig. 5b, c. By using wrapped STF/foam layers in the composites (Config-9 and Config-10), it is possible to reduce the target mass with respect to the full-cork agglomerates (Config-3 and Config-4). Mass of the structures reduces from 46.5 g (Config-3) to 43.4 g (Config-9) for three-layer configurations while it is from 62.0 g (Config-4) to 55.8 g (Config-10) for four-layer configurations. These changes correspond to mass reduction ratios of 6.7% and 10% for three-layer and four-layer configurations

Fig. 8 Cell crushing in cork and foam microstructures after impact
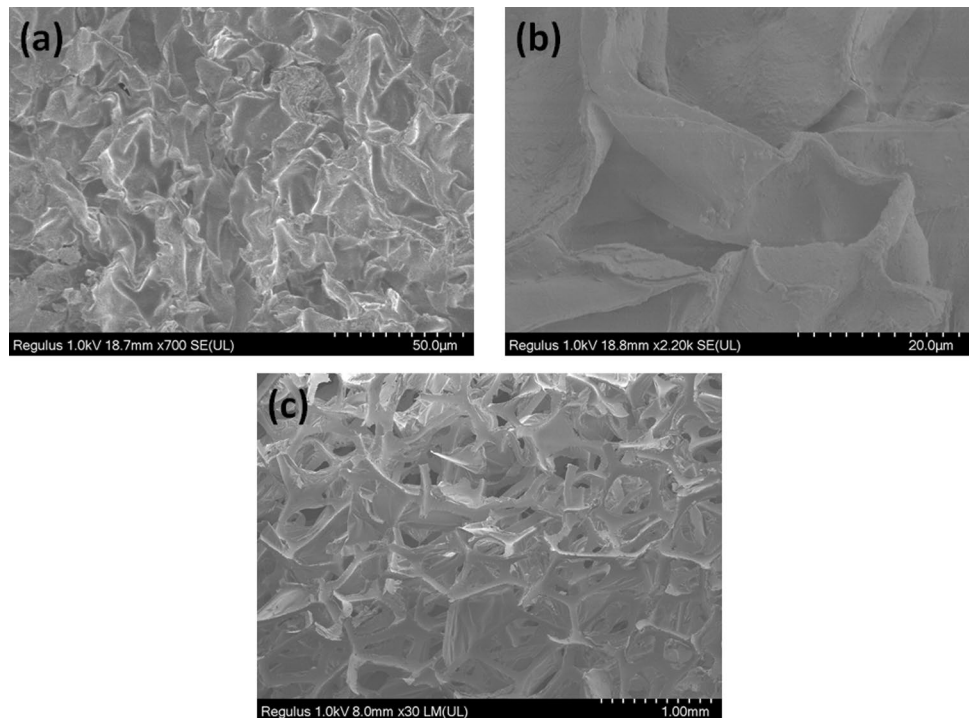
respectively. Despite the mass losses, the configurations including wrapped STF/foam layers exhibit lower peak decelerations in comparison to full-cork agglomerates for drop heights of 0.5 and 1.0 m.

In addition to peak deceleration, another important factor is rate of deceleration in safety applications. Impact curves should be with low peaks and large bases not to have sharp deceleration rates [8]. Figure 9 shows the deceleration vs time curves for drop height of 1 m. Comparing the configurations from 1 to 4, we can analyze the role of number of cork layers in the composites. From the curve of one-layer cork agglomerate (Config-1), there are two successive peaks, where the first one is the main contact with impactor and the subsequent one is related to structure thickness. The second peak stems from stress transition from impactor to load cell beneath the cork layer. By increasing thickness with additional cork layers, deceleration rate (curve slope) slightly reduces and peak base extends to a longer span of time. At this stage, stress transition at the bottom of cork agglomerates coincides with the first peak zone while gradually fading away due to the increased thickness. Consequently, the second peak is covered by the first one and deceleration characteristics is described by only one peak as shown in the thicker configurations. By adding neat foam layers as is the case with Config-5 and Config-6, peak durations show almost no change compared to full-cork agglomerates of Config-3 and Config-4 respectively. However, STF inclusion into foam layers (Config-7 and Config-8) slightly extends the deceleration process. This effect is more pronounced in Config-8 than Config-7 due to higher amount of STF. Despite spilling out of foam layers, remaining STF shows thickening phenomenon during impact and thereby distributing the impact loading over a wider area. This process prevents the impacting object from sharp loading. In Config-9 and Config-10, where wrapped STF/foam layers are used, deceleration processes exhibit further extensions while reducing curve slopes and peak points. In the enveloped liquid medium, shear thickening process grows stronger due to the increased internal pressure. For this reason, hydro-clustering is able to spread all over the foam layer. Distribution of loading on the foam layer is enhanced and therefore, far-fields contribute to attenuation mechanism. This means that impacting object is avoided sharp loading in a very limited time. Hence, possible damages on the impacting objects are effectively eliminated.

4 Conclusions

In the present work, deceleration behavior of multi-layer composites was studied. Due to great energy absorbing capabilities as well as eco-friendly properties, cork layers were selected as main component in the structures. The composites were also intercalated with a non-Newtonian material, STF to benefit from its rheological behavior. Since STF is a fluidic material, foam layers were used to contain this smart material in the assemblies. A further process was carried out by wrapping STF impregnated foam layers to avoid spilling

Fig. 9 Deceleration vs time curves for drop height of 1 m
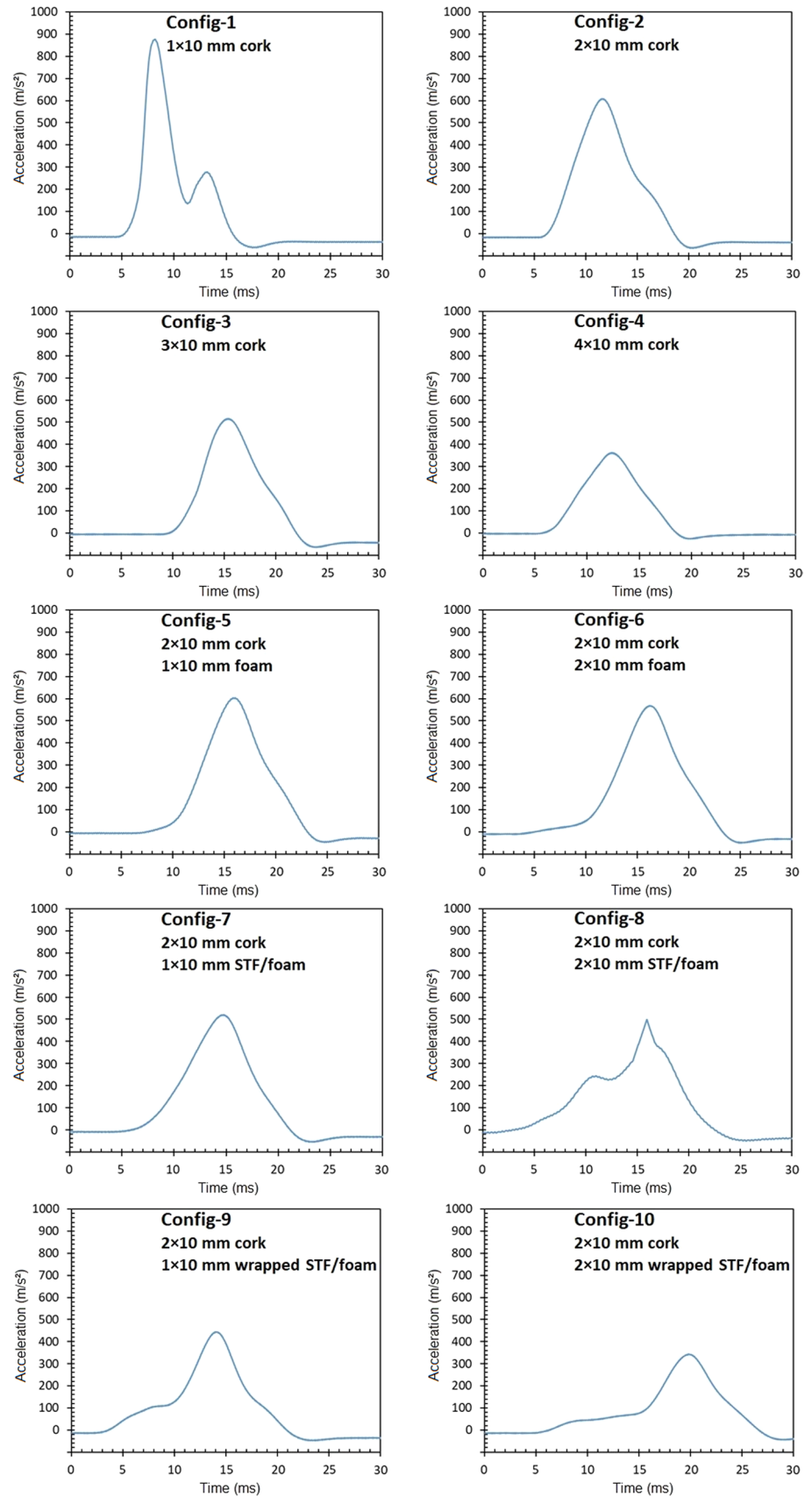
during impact. According to the results, the configurations with neat foam and STF/foam layers show a loss of performance in comparison to full-cork structures. However, peak decelerations are lowered by using wrapped STF/foam layers in the composites. Wrapping provides an enveloped medium for STF in foam and thereby enhancing shear thickening formation due to increased internal pressure upon impact. Hence, thickened suspension acts as a continuous matrix from impact point to far-fields in foam layer. For this reason, impact loading is efficiently distributed over the structure and consequently, peak deceleration is lowered by the contribution of shear thickening rheology.

Author contributions   Conceptualization: SG; methodology: SG; writing-reviewing and editing: SG; investigation: MRS; data curation: MRS.

Data availability   The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

Code availability   Not applicable.

Declarations

Conflict of interest   The authors declare that there is no conflict of interest.

Ethical approval   This article does not contain any studies with human participants or animals performed by any of the authors.

References

1. Sareh P, Chermprayong P, Emmanuelli M, Nadeem H, Kovac M. Rotorigami: a rotary origami protective system for robotic rotorcraft. Sci Robot. 2018;3(22):eaah5228. https://doi.org/10.1126/scirobotics.aah5228.

2. Gürgen S, Fernandes FAO, de Sousa RJA, Kuşhan MC. Development of eco-friendly shock-absorbing cork composites enhanced by a non-Newtonian fluid. Appl Compos Mater. 2021;28(1):165–79. https://doi.org/10.1007/s10443-020-09859-7.

3. Sheikhi MR, Gürgen S. Anti-impact design of multi-layer composites enhanced by shear thickening fluid. Compos Struct. 2022;279: 114797. https://doi.org/10.1016/j.compstruct.2021.114797.

4. Duque-Lazo J, Navarro-Cerrillo RM, Ruíz-Gómez FJ. Assessment of the future stability of cork oak (*Quercus suber* L.) afforestation under climate change scenarios in Southwest Spain. For Ecol Manag. 2018;409:444–56. https://doi.org/10.1016/j.foreco.2017.11.042.

5. Silva SP, Sabino MA, Fernandes EM, Correlo VM, Boesel LF, Reis RL. Cork: properties, capabilities and applications. Int Mater Rev. 2005;50(6):345–65. https://doi.org/10.1179/174328005X41168.

6. Gil L. Cork composites: a review. Materials. 2009;2(3):776–89. https://doi.org/10.3390/ma2030776.

7. Fernandes FAO, Jardin RT, Pereira AB, Alves de Sousa RJ. Comparing the mechanical performance of synthetic and natural cellular materials. Mater Des. 2015;82:335–41. https://doi.org/10.1016/j.matdes.2015.06.004.

8. Jardin RT, Fernandes FAO, Pereira AB, Alves de Sousa RJ. Static and dynamic mechanical response of different cork agglomerates. Mater Des. 2015;68:121–6. https://doi.org/10.1016/j.matdes.2014.12.016.

9. Crouvisier-Urion K, Bellat J-P, Gougeon RD, Karbowiak T. Mechanical properties of agglomerated cork stoppers for sparkling wines: influence of adhesive and cork particle size. Compos Struct. 2018;203:789–96. https://doi.org/10.1016/j.compstruct.2018.06.116.

10. Kaczynski P, Ptak M, Wilhelm J, Fernandes FAO, de Sousa RJA. High-energy impact testing of agglomerated cork at extremely low and high temperatures. Int J Impact Eng. 2019;126:109–16. https://doi.org/10.1016/j.ijimpeng.2018.12.001.

11. Lagorce-Tachon A, Karbowiak T, Champion D, Gougeon RD, Bellat J-P. How does hydration affect the mechanical properties of wine stoppers? J Mater Sci. 2016;51(9):4227–37. https://doi.org/10.1007/s10853-015-9669-6.

12. Ptak M, Kaczynski P, Fernandes FAO, de Sousa RJA. Assessing impact velocity and temperature effects on crashworthiness properties of cork material. Int J Impact Eng. 2017;106:238–48. https://doi.org/10.1016/j.ijimpeng.2017.04.014.

13. Fernandes F, Alves de Sousa R, Ptak M, Migueis G. Helmet design based on the optimization of biocomposite energy-absorbing liners under multi-impact loading. Appl Sci. 2019;9(4):735. https://doi.org/10.3390/app9040735.

14. Serra GF, Fernandes FAO, Noronha E, de Sousa RJA. Head protection in electric micromobility: a critical review, recommendations, and future trends. Accid Anal Prev. 2021;163: 106430. https://doi.org/10.1016/j.aap.2021.106430.

15. Fernandes FAO, Tavares JP, Alves de Sousa RJ, Pereira AB, Esteves JL. Manufacturing and testing composites based on natural materials. Proc Manuf. 2017;13:227–34. https://doi.org/10.1016/j.promfg.2017.09.055.

16. Gürgen S, Kuşhan MC. The effect of silicon carbide additives on the stab resistance of shear thickening fluid treated fabrics. Mech Adv Mater Struct. 2017;24(16):1381–90. https://doi.org/10.1080/15376494.2016.1231355.

17. Gürgen S, Kuşhan MC. The stab resistance of fabrics impregnated with shear thickening fluids including various particle size of additives. Compos Part Appl Sci Manuf. 2017;94:50–60. https://doi.org/10.1016/j.compositesa.2016.12.019.

18. Gürgen S. Numerical modeling of fabrics treated with multi-phase shear thickening fluids under high velocity impacts. Thin-Walled Struct. 2020;148: 106573. https://doi.org/10.1016/j.tws.2019.106573.

19. Gürgen S, Kuşhan MC. The ballistic performance of aramid based fabrics impregnated with multi-phase shear thickening fluids. Polym Test. 2017;64:296–306. https://doi.org/10.1016/j.polymertesting.2017.11.003.

20. Gürgen S, Yıldız T. Stab resistance of smart polymer coated textiles reinforced with particle additives. Compos Struct. 2020;235: 111812. https://doi.org/10.1016/j.compstruct.2019.111812.

21. Gürgen S. An investigation on composite laminates including shear thickening fluid under stab condition. J Compos Mater. 2019;53(8):1111–22. https://doi.org/10.1177/0021998318796158.

22. Gürgen S, Sofuoğlu MA. Smart polymer integrated cork composites for enhanced vibration damping properties. Compos Struct.

2021;258: 113200. https://doi.org/10.1016/j.compstruct.2020.113200.

23. Gürgen S, Kuşhan MC, Li W. Shear thickening fluids in protective applications: a review. Prog Polym Sci. 2017;75:48–72. https://doi.org/10.1016/j.progpolymsci.2017.07.003.

24. Gürgen S, Kuşhan MC, Li W. The effect of carbide particle additives on rheology of shear thickening fluids. Korea-Aust Rheol J. 2016;28(2):121–8. https://doi.org/10.1007/s13367-016-0011-x.

25. Bergström L. Shear thinning and shear thickening of concentrated ceramic suspensions. Colloids Surf Physicochem Eng Asp. 1998;133(1–2):151–5. https://doi.org/10.1016/S0927-7757(97)00133-7.

26. Gürgen S, Li W, Kuşhan MC. The rheology of shear thickening fluids with various ceramic particle additives. Mater Des. 2016;104:312–9. https://doi.org/10.1016/j.matdes.2016.05.055.

27. Gürgen S, Sofuoğlu MA, Kuşhan MC. Rheological compatibility of multi-phase shear thickening fluid with a phenomenological model. Smart Mater Struct. 2019;28(3): 035027. https://doi.org/10.1088/1361-665X/ab018c.

28. Melrose JR, Ball RC. Continuous shear thickening transitions in model concentrated colloids—the role of interparticle forces. J Rheol. 2004;48(5):937–60. https://doi.org/10.1122/1.1784783.

29. Shamsadinlo B, Sheikhi MR, Unver O, Yildirim B. Numerical and empirical modeling of peak deceleration and stress analysis of polyurethane elastomer under impact loading test. Polym Test. 2020;89: 106594. https://doi.org/10.1016/j.polymertesting.2020.106594.

30. Gürgen S, de Sousa RJA. Rheological and deformation behavior of natural smart suspensions exhibiting shear thickening properties. Arch Civ Mech Eng. 2020;20(4):110. https://doi.org/10.1007/s43452-020-00111-4.