DYNAMIC RESPONSE OF WOOD-BASED BIOCOMPOSITIES UNDER HIGH-STRAIN RATE COMPRESSIVE LOADING

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(Received April 2017)

Abstract. This paper focuses on obtaining a high-strain compressive response of various wood-based biocomposites. The dynamic stress-strain curves of various wood-based biocomposites at three different strain rates were obtained using a split-Hopkinson pressure bar (SHPB) and were compared. The specific energy of each composite sample at three different strain rates was obtained and compared. It was found that 4% methylene diphenyl diisocyanate (MDI), 4% processed corn starch (CS) 600S had the highest specific energy for all nine different kinds of wood-based biocomposites tested in this study. The panel produced with 4% MDI and formed at the highest pressure (mat pressure of 1523 psi) consistently had the highest yield strength in the Hopkinson bar tests conducted at 10 psi (560-1053 s^{-1}, was the range of strain rate achieved under this pressure), 15 psi (727-1380 s^{-1}, was the range of strain rate achieved under this pressure), and

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Wood and Fiber Science, 49(4), 2017, pp. 444-452

20 psi (766-15837 s^{-1}, was the range rate of strain achieved under this pressure). When comparing samples that were formed under similar mat pressures, the material formed at the longest curing time (600 s) had the highest yield strength at 10 psi. At similar mat pressures, when tested at 15 psi, the material formed from 2% CS and 4% MDI at 140 s had the highest yield strength. At similar mat pressures, when tested at 20 psi, the material formed from 2% CS and 2% MDI at 140 s had the highest yield strength. Samples containing CS had a high average strain rate when compared with other wood samples, and this shows that the CS contributed to the high stain rate of the material.

Keywords: Split-Hopkinson pressure bar, high-strain rate behavior, wood, biocomposites, methylene diphenyl diisocyanate (MDI), micro-crystalline cellulose (MCC).

INTRODUCTION

This research focuses onthe results obtained from a split-Hopkinson pressure bar (SHPB) experiment performed on several wood-based biocomposites. Characterizing the material behavior at a high strain rate is an important aspect. Afrough et al (2015) found the behavior of pultruded glass-graphite/epoxy hybrids under transverse high-strain rate compression loading. Their research found that failure of specimens loaded along transverse direction was dominated by matrix failure. Their study also showed that the ultimate compressive strength was marginally increased by including a higher percentage of graphite. To safely transport nuclear waste and toxic matter, it is required that the material be protected from dynamic loading situations. Wood can be used for such applications Allazadeh and Wosu (2011). They studied the response of dry maple wood under a high-strain rate compressive impact load. The deformation of the maple specimen was found to be a linear function of energy absorption. The dynamic response of four (borosilicate, soda lime, starphire, and fused silica) commercially available glasses was studied under high-strain rate compressive loading. The results showed that the compressive strength was very sensitive to strain rate, whereas the stiffness remained constant Daryadel et al (2014). Bragov and Lomunov (1997) obtained dynamic deformation diagrams for pine, birch, and lime using a SHPB. They found that the deformation diagrams were nonlinear and differ in their loading and unloading brunches. It was also found that the stress values resulted in cracking and spallation.

Resources from forests are a major asset to Mississippi and the southeastern United States. Around 19.7 million acres (65%) of the total land area of Mississippi is covered by forests (Dahal et al 2013). Thus, developing wood-based products is an important aspect when wood is produced in such a large quantity. New wood-based biocomposites were developed in collaboration with the Department of Sustainable Bioproducts, Mississippi State University. Nine different kinds of wood-based biocomposites were produced by combining various amount of methylene diphenyl diisocyanate (MDI), corn starch (CS), and microcrystalline cellulose (MCC) for various compression periods and various compression pressures. Extensive research has been done in the area of biocomposites because this area has many advantages including the low manufacturing costs involved in producing the final products and producing highly valued products from low-value material. Producing biodegradable products has become a necessity due to petroleum-based products being a finite resource and having more potential to harm the environment. Biocomposites are beneficial because the disposition of the biofibers is not complex and they are natural organic products, which do not pose a biohazard compared with other conventional available fibers. The density of the bio fibers is lower when compared with glass fibers, and they also have thermal insulating and acoustic properties (because of their hollow tubular structure). In this research, the high stain rate compression behavior was studied for nine different biocomposite samples. An SHPB (Kolsky 1949; Weinong and Bo 2011; Ramesh, 2008) was used to obtain the dynamic behavior of different biocomposite samples under high-strain rate compressive loading. A high-speed camera was used to capture the behavior of all the wood configurations under the three

Table 1. Nine samples dynamically tested with the split-Hopkinson bar procedure.

No.	Type of wood-based biocomposite	Curing time (s)	Compression pressure (psi)
1	4% MDI	140	1294
2	4% MDI, 1% MCC	140	1332
3	4% MDI, 2% MCC	140	1028
4	2% MDI, 2% CS	140	1256
5	2% MDI, 4% CS	140	1332
6	4% MDI, 2% CS	140	1332
7	4% MDI, 4% CS	140	1218
8	4% MDI, 4% CS	600	1370
9	4% MDIHP (high pressure) with 2× more material	140	1523

loading conditions. The ultimate goal of the research was to replace conventional construction materials with these types of biocomposites, which have improved properties.

MATERIALS

The dynamic response under high-strain rate compression was studied for nine different kinds of wood-based biocomposites as shown in Table 1. Three replicates of the specimens were tested. The original panel formed from the material measured 508 mm × 559 mm. Specimens were then cut from the center of this panel and measured approximately 12.7 mm × 12.7 mm × 6.7 mm. Table 1 displays the nine different wood-based biocomposite compositions tested. The total water content in each mat before being pressed was approximately 6 wt%. The percentages shown in Table 1 refer to the solids content in the panel, with the remaining percentage being southern yellow pine. Pure cotton was processed into MCC using methods outlined in a previous study using an HCl solution at 85°C and continuous stirring for 1.5 h (Chauhan et al 2009). Pure CS was obtained and used for panels 4-8.

EQUIPMENT AND EXPERIMENTAL PROCEDURE

A Dieffenbacher hot press system (450 ton, 34″ × 34″, PressMAN system, Alberta Research Council, Edmonton, Alberta, Canada) located at the Sustainable Bio products Laboratory at Mississippi State University was used to create the panels used in this study. The ram had an area

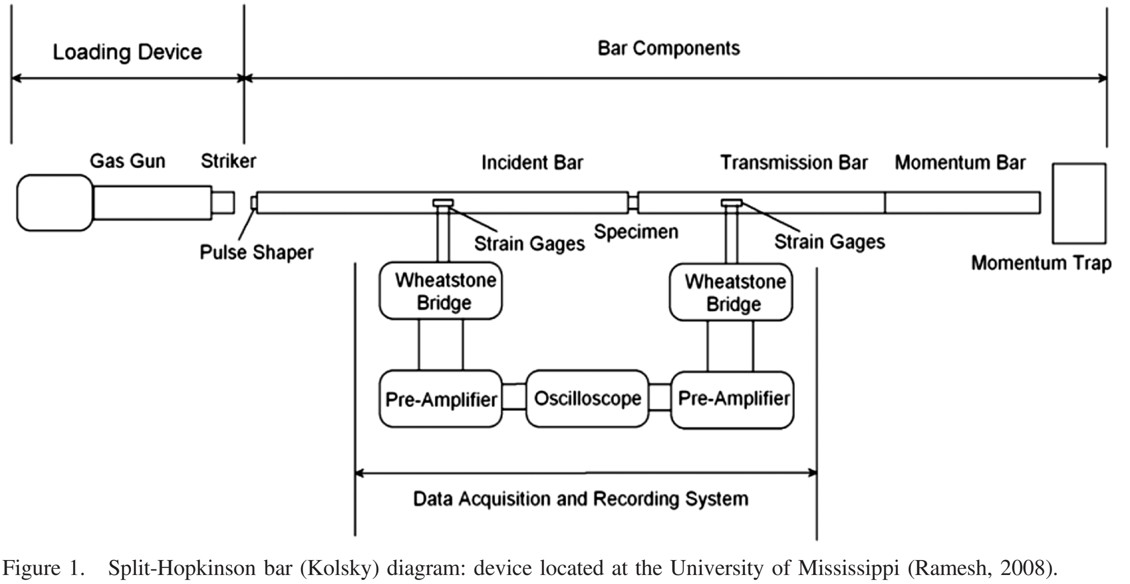

Figure 1. Split-Hopkinson bar (Kolsky) diagram: device located at the University of Mississippi (Ramesh, 2008).

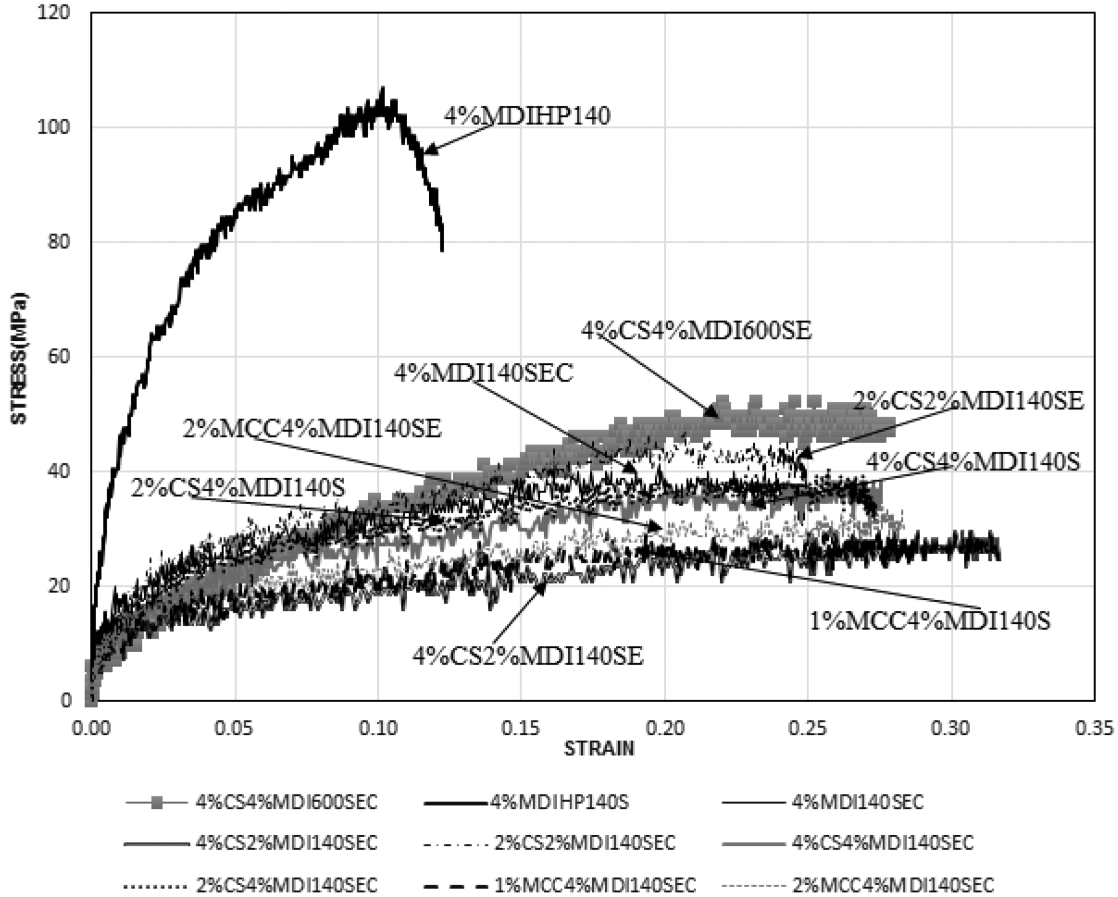

Figure 2. Dynamic stress-strain curve of wood-based biocomposites at 10 psi (strain rate from 560 to 1053 s^{-1}).

of 201.0619 in^2, a 40-HP motor and a pump size of 71 mL/rev. This hot press with steam injection capability was coupled with the Alberta Research Council's Pressman operation and monitoring software. The same amount of material was used to form the panels (except twice the amount of material was used to produce panel no 9), and the press was programmed to produce a panel with a particular thickness (6.35 mm).

A Kolsky bar or SHPB was used to obtain the dynamic behavior of the composites under three ranges of strain rate (varying from 560 to 1568 s^{-1}). The experiments were carried out at the Blast and Impact Dynamics lab, University of Mississippi, a schematic of the same is shown in Fig 1. Aluminum bars with a 19.02-mm diameter and an annealed copper pulse shaper were used between the striker and the incident bar to ramp up the incident pulse and slow down the rate of loading. This method allowed the samples to be dynamically loaded at an equilibrium stress state. A pulse shaper was placed between the incident bar and the striker bar, so when the striker bar would strike the incident bar, the pulse shaper would come between the striker and the incident bar. The specimen was placed between the incident bar and the transmission bar and then the striker bar was launched to impact the pulse shaper and incident bar. Three replicates of each type of biocomposite were tested. The high-strain rate compression experienced by each kind of composite was recorded by high-speed cameras.

Different strain rates (varying from 560 to 1568 s^{-1}) were obtained by varying the pressure of the compressed air in the Hopkinson bar. The pressures used for this purpose were 10, 15, and 20 psi. Figure 1 shows a schematic diagram of the SHPB.

EXPERIMENTAL RESULTS AND DISCUSSION

The dynamic relationship of the wood composite samples at 10 psi (560-1053 s^{-1}, was the range of strain rate achieved under this pressure) is shown in Fig 2. It was observed that the maximum strain was 0.30. Here it was observed that the 4%CS2%MDI140S sample had the lowest yield strength and the 4%MDIHP140S sample had the highest yield strength. When comparing samples which were formed under the similar pressure, the 4%CS4%MDI600S sample had the highest yield strength. When comparing samples, which were formed under the *similar* pressure and curing time, the 2%CS2%MDI140S sample had the highest yield strength. These results varied when the strain rate was changed.

Figure 3 shows the dynamic stress-strain curve of the wood-based biocomposites at 15 psi (727-1380 s^{-1}, was the range of strain rate achieved under this testing pressure). This graph shows that the 4%MDI140S sample had the lowest yield strength, and the trend of the stress-strain curve differed slightly in comparison with the stress-strain curve at 10 psi. The 4%MDIHP140S sample still showed the highest yield strength.

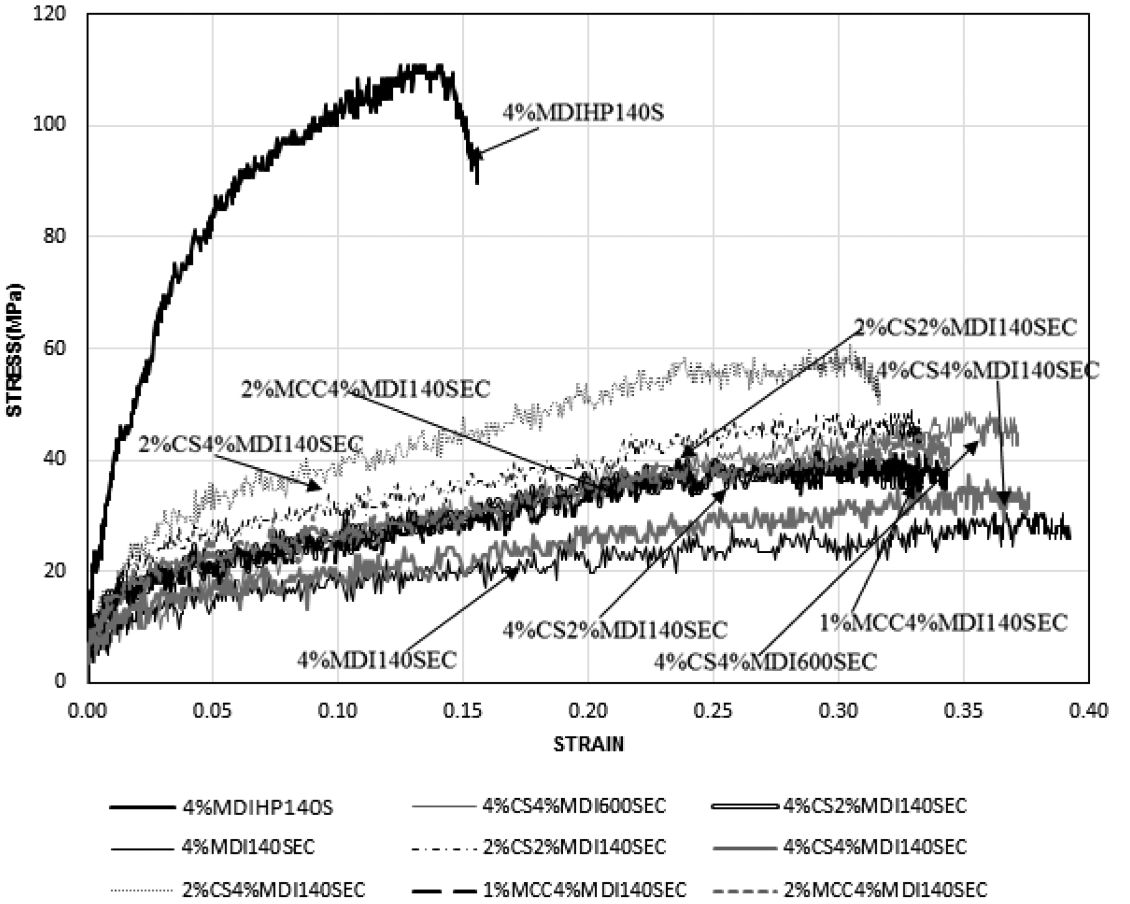

Figure 3. Dynamic stress-strain curve of wood-based biocomposites at 15 psi (strain rate from 727 to 1380 s^{-1}).

Here the maximum strain increased to 0.39. When comparing samples, which were formed under the *similar* pressure and curing time, the 2%CS4%MDI140S sample had the highest yield strength. The 4%MDI140S sample had the largest strain compared with other wood samples.

Figure 4 shows the dynamic stress-strain curve of the composites tested at 20 psi (766-15837 s^{-1}, was the range of strain rate achieved under this pressure). The sample that was formed under the highest pressure (4%MDIHP140S) had the highest yield strength, whereas the sample containing 1% MCC had the lowest yield strength. When comparing samples, which were formed under the *similar* pressure and curing time, the 2%CS2% MDI140S sample had the highest yield strength. The samples containing CS consistently show a higher yield strength when compared with samples containing MCC. The stress-strain relationship shows that each sample (except for the 4%MDIHP140S) is highly plastic. This result shows that each of these samples has an incompressibility property of plastic deformation and is highly incompressible. As these samples were being plastically deformed, they experienced a shape change when loading was experienced because plastic strain was responsible for their shape change. However, the 4%MDIHP140S sample was shown to be highly elastic. High elastic strain in the 4%MDIHP140S sampled induced a volume change, so this sample was highly compressible. The curing period while

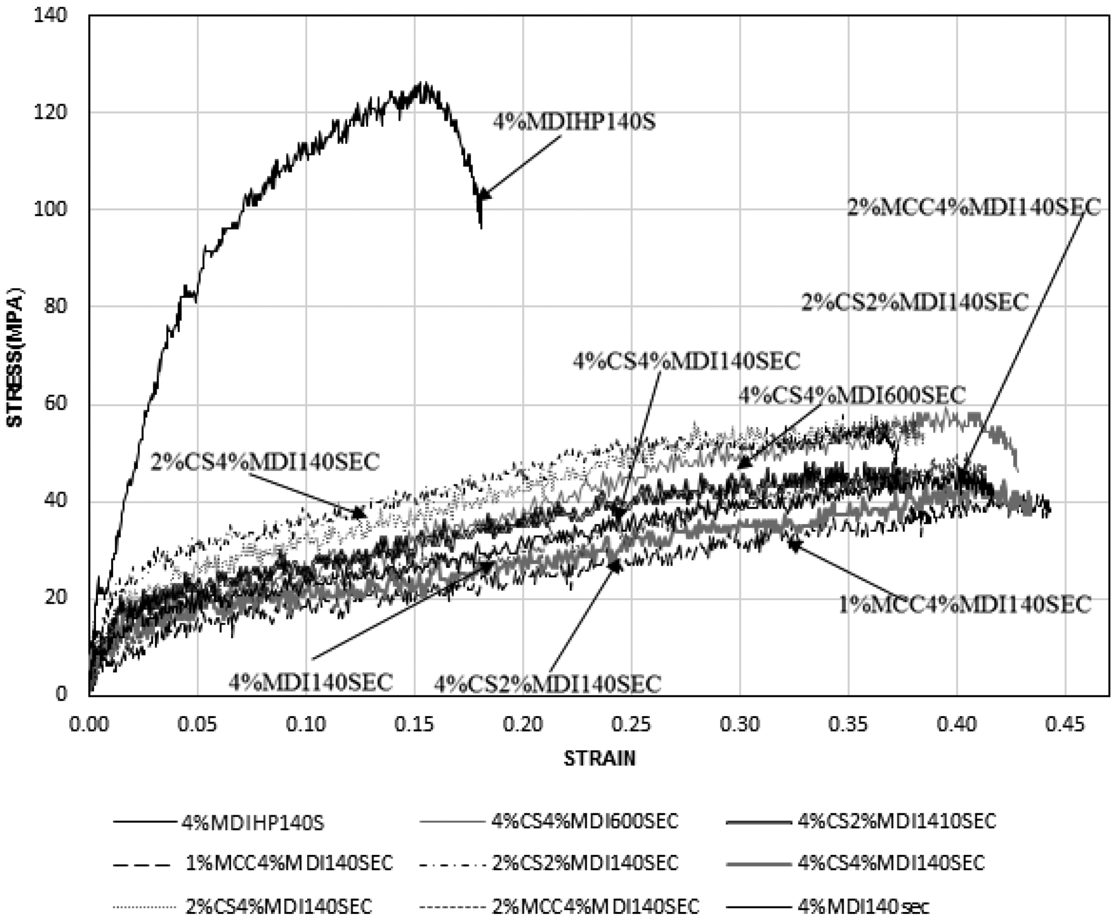

Figure 4. Dynamic stress-strain curve of wood-based biocomposites at 20 psi (strain rate from 766 to 1587 s^{-1}).

fabricating the samples did not play a major role in behavior of the wood composite, and this is seen when the 4%MDI140S, 4%CS4%MDI140S, and 4%CS4%MDI600S are compared. From the dynamic stress-strain relationship, it was observed that the stress-strain curve of the 4%MDIHP140S composted was clearly differentiated from the rest of stress-strain curves. This shows that the amount of pressure applied during the fabrication process had a large effect on the dynamic response of the wood. The "4%MDIHP140S" sample had a much greater stiffness value in comparison with the other samples. All of the samples were flexible in comparison with the "4%MDIHP140S" sample.

The results illustrate that the entire specimen has not been extensively damaged at the peak stress. It appears that compression failure is dominated by plastic deformation at peak load followed by debonding of the interface between constituents. In Fig 5a, stress-strain curves for 4%MDI HP140S are plotted for the three different strain rates. It can be observed that material behavior is dependent on the applied strain rate on to the specimen during the SHPB experiment. For 4%MDI HP 140S, at a highest strain rate of 793 s^{-1}, the peak stress was observed around 105 MPa, which is 25 psi higher than the peak stress observed at a lower strain rate of 600 s^{-1}. In Fig 5b,

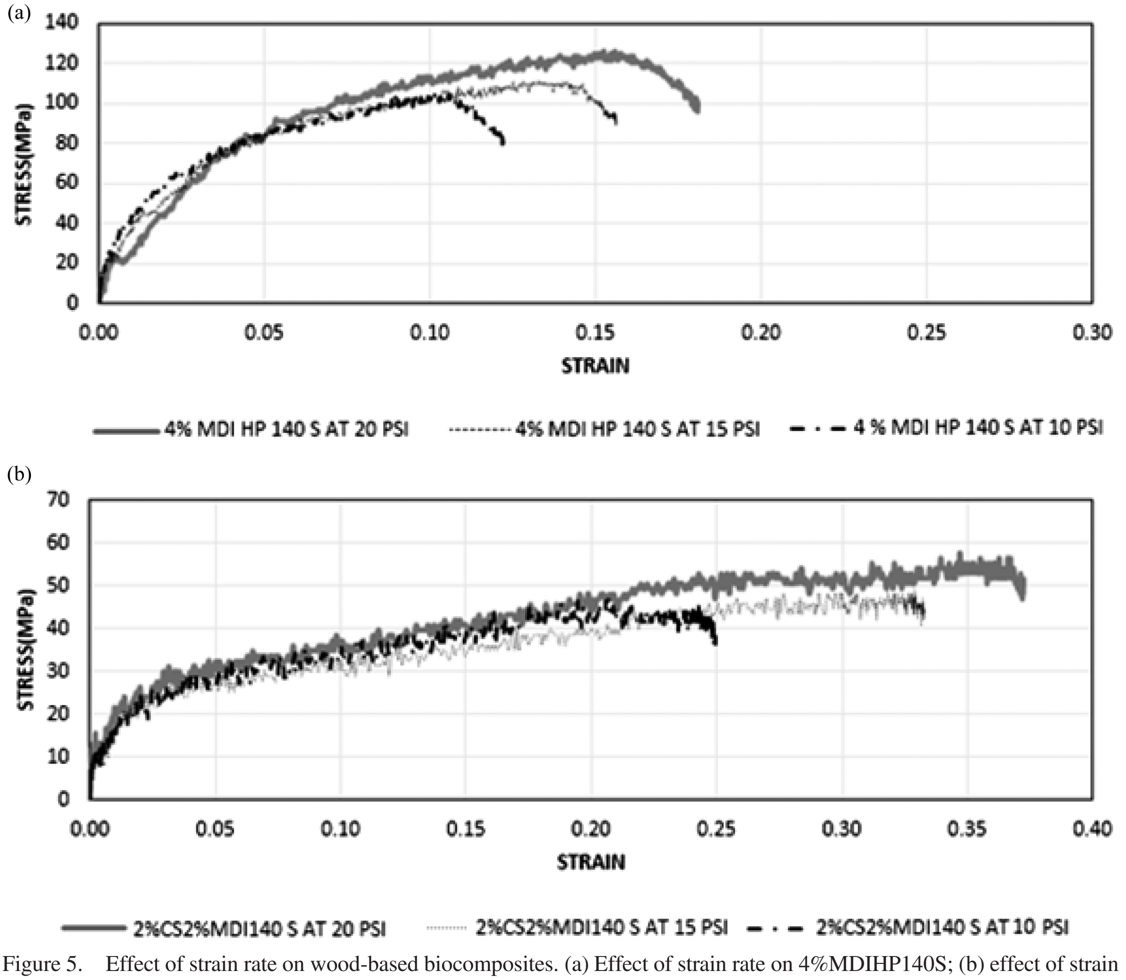

Figure 5. Effect of strain rate on wood-based biocomposites. (a) Effect of strain rate on 4%MDIHP140S; (b) effect of strain rate on 2%CS2%MDI140S.

Table 2. Average strain rate and specific energy at different strain rates.

No.	Type of wood-based biocomposite	Average strain at 10 psi (s^{-1})	Specific energy at 10 psi (kJ/kg)	Average strain at 15 psi (s^{-1})	Specific energy at 15 psi (kJ/kg)	Average strain at 20 psi (s^{-1})	Specific energy at 20 psi (kJ/kg)
1	4%MDIHP140S	600 ± 30.9	10.6 ± 1.38	709.3 ± 19	13.1 ± 0.12	793 ± 56.9	17.2 ± 1.4
2	4%MDI4%CS600S	1143.3 ± 92	15.1 ± 1.5	13545 ± 16.7	18.8 ± 0.2	1644.7 ± 68.9	26.6 ± 1.6
3	4%MDI140S	857.5 ± 4.9	11.01 ± 0.2	1113 ± 16.9	15.9 ± 0.3	1209.7 ± 11.5	20 ± 0.1
4	2%MDI4%CS140S	943.5 ± 25.1	11.13 ± 0.34	1267 ± 6	15.3 ± 0.1	1454.5 ± 76.7	19.2 ± 0.4
5	2%MDI2%CS140S	947 ± 25.8	11.9 ± 0.04	1236.25 ± 4.1	16.9 ± 0.2	1373.66 ± 15.5	21.7 ± 0.15
6	4%MDI4%CS140S	930 ± 1.8	12.38 ± 0.35	1195.3 ± 32.2	16.5 ± 0.5	1335.7 ± 79.7	19.6 ± 1.8
7	4%MDI2%CS140S	1055.3 ± 44.9	11.9 ± 0.3	1175 ± 9.1	18.9 ± 0.2	1546 ± 14	20.43 ± 0.7
8	4%MDI1%MCC140S	887 ± 8.5	11.01 ± 0.2	1143 ± 19.8	17.5 ± 0.5	1248.33 ± 16.6	22.08 ± 0.5
9	4%MDI2%MCC140S	1063.75 ± 9.1	11..3 ± 0.2	1258.75 ± 21.7	16.2 ± 0.4	1571 ± 18.7	20.5 ± 0.15

stress-strain curves for 2%CS2%MDI 140S are plotted for the three different strain rates. It can be observed that material behavior is independent of the applied strain rate on the specimen during the SHPB experiment. There was not much difference in the peak stress at the three different strain rates. It was observed that material yielded without much variation in the stress. The same materialistic behavior was observed in the other seven materials as observed in Fig 5b.

Table 2 shows that the 4%MDI4%CS 600S sample had the highest average strain rate. This was followed by the 4%MDI1%MCC140S sample at all the three loading pressures. Samples containing CS had a high average strain rate when compared with other wood samples, and this shows that the CS contributed to the high stain rate of the material. The 4%MDIHP140S sample had the lowest strain rate, and the 4%MDI140S sample consistently had a high strain rate. This shows that compression pressure applied during the fabrication process of the wood composite plays a major role in enhancing these properties. The specific energy for the 4% MDI4%CS 600S sample was the highest among all the samples. The samples containing CS also had an important role in the specific energy of the material. The lowest specific energy was found from the control sample, 4%MDIHP140S, and this again proves that how highly elastic this material is.

CONCLUSION

Nine wood-based biocomposites were studied for high-stain rate compressive loading using the SHPB test. It was found that the composite created at the highest pressure (4%MDIHP140S) had the greatest stiffness among all the samples. This shows that improved composite stiffness can be achieved when material is compressed at a higher pressure during the fabrication process. The sample containing a solid content of 4% MDI and 4% CS pressed at 600 s had the highest average strain rate and specific energy. The samples containing CS showed enhanced properties, and therefore CS can be a good constituent for making wood-based biocomposites. The applications of these samples can be various including being used as packaging material where they can sustain dynamic impact.

FUTURE SCOPE

DIC analysis can be done on all the wood samples. The following wood samples can be studied under blast loading.

ACKNOWLEDGMENTS

We would like to express gratitude to Dr. P. Raju Mantena for his input throughout this research and Matthew Lowe for processing the wood-based composite samples. The authors wish to acknowledge the support of the U.S. Department of Agriculture (USDA), Research, Education, and Economics (REE), Agriculture Research Service (ARS), Administrative and Financial Management (AFM), Financial Management and Accounting Division (FMAD) Grants and Agreements Management Branch (GAMB), under Agreement No. 5B-0202-4-001. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the U.S. Department of Agriculture. This material is supported by the USDA. National Institute of Food and Agriculture and McIntire Stennis under 1008126. Research reported in this publication was supported, in part, by the McLean Institute for Public Service and Community Engagement at the University of Mississippi, through a Robert M. Hearin Support Foundation grant award for the Catalyzing

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