INTRAPLY HYBRID COMPOSITES BASED ON BASALT AND NYLON WOVEN FABRICS: TENSILE AND COMPRESSIVE PROPERTIES

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Abstract: *In this study, the tensile and compressive behaviors of pure and hybrid composite laminates reinforced by basalt–nylon bi-woven intra-ply fabrics were experimentally investigated. Epoxy resin was used as the matrix material. The purpose of using this hybrid composite is to obtain superior characteristics by using the good strength property of basalt fiber with the excellent toughness of nylon fiber. Five different types of woven fabric were used as reinforcement with different volume percentages of nylon (0%, 25%, 33.3%, 50% and 100%). The effects of nylon/basalt fiber content on tensile and compressive parameters were studied. In addition, the after failure visual inspection and scanning electron microscopy (SEM) analysis was used to determine the extent and type of damage on tested specimens. The results indicate that the tensile and compressive performances of these composites are strongly affected by the nylon/basalt fiber content. Also, with a proper choice of fiber content, the nylon/basalt hybrid composites can achieve mechanical properties comparable with the pure ones. The stress–strain curves, after failure visual inspection and SEM analysis of tested specimens reveal that hybridization can prevent catastrophic and complete failure. In hybrid composites, the basalt and nylon fibers cannot reach their maximum strength at the same time and the progressive failure of the various fibers therefore occurred.*

Keywords: *Intra-ply; Hybrid; Tensile; Compressive; Basalt; Nylon*

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1. INTRODUCTION

Hybrid composites are defined as composites containing more than one type of fiber. Hybrid composites were proved to achieve properties superior to those of pure composites especially as regards specific properties. With the proper hybrid combination of reinforcements, the possibility of controlling many composite properties at the same time increases, and some disadvantages of composites reinforced by one type of fiber can be improved [1, 2].

Nowadays, the main reinforcing materials of structural polymer composites are glass and carbon fibers. It has been proved in the last few years that, due to the disadvantages of the two conventional reinforcing fibers, new types of fiber can be used. As a result of intensive scientific research around the world, the use of mineral fibers such as basalt fiber has been spreading as a replacement for the aforementioned two reinforcing fibers. Basalt fiber has good strength, modulus, thermal and chemical properties [2-4]. Mechanical properties of basalt-fiber-reinforced composites have been investigated in a few studies. Among the publications in this subject area, Carmisciano [3], Lopresto [4], Liu [5], Sarasini [6] and Artemenko [7] claimed that the mechanical properties of basalt are better than those of glass fibers. Eslami [8], Czigany [9] and Ozturk [10] investigated mechanical properties such as tensile, flexural and Izod impact properties of intimately hybrid composites made of basalt and different fibers. Wang [11] and Tehrani [12, 13] studied impact properties of basalt/kevlar and basalt/nylon intra-ply hybrid composites, respectively.

Nylon-fiber-reinforced composites are attractive materials because of their high impact resistance and they are much used in military applications such as for body armor. On the other hand, this material has the disadvantage of being tensile, flexural, and its thermal properties are poor [14]. To compensate for the defects of basalt and nylon-reinforced composites, nylon/basalt hybrid composites have been manufactured and characterized. One of the most important purposes of using this hybrid composite is to obtain superior characteristics by combining the good strength property of basalt fiber with the excellent toughness of nylon fiber.

According to the geometric pattern of fiber arrangements, hybrid composites can be conveniently classified as inter-ply hybrids where layers of the two (or more) pure reinforcements are stacked, intra-ply hybrids in which tows of the two (or more) constituent types of fibers are mixed in the same layer, and intimately mixed hybrid where the constituent fibers are mixed as randomly as possible [12, 15]. The mechanical properties of inter-ply and intimately mixed hybrid composites have been investigated by many researchers [9, 15, 16]. The mechanical properties of intra-ply hybrid composites have not been studied extensively. Among a few publications in this subject area, Zeng et al. [17] studied stress concentrations in a carbon-glass/epoxy intraply hybrid composite sheet. Chamis et al. [18], Pegoretti et al. [15], Park and Jang [19] and Wang [11] investigated mechanical properties such as tensile, flexural, interlaminar shear and Izod impact properties of intraply hybrid laminates made of different fibers. Akhbari [20] and Tehrani [12, 13] studied low velocity drop impact and CAI of ductile/brittle fiber intraply hybrid composites.

During our previous work, the low velocity impact behavior of homogenous and hybrid composite laminates reinforced by basalt–nylon intra-ply fabrics was experimentally investigated. The results of these studies indicate that hybridization and variation in basalt/nylon fiber content can improve the impact performance of composite plates [12, 13]. Any way, approximately in all application of composite materials, the mechanical properties such as tensile and compressive properties are important. When this information is applied to the real systems, design of the new composite material structures could be possible. In this paper, the tensile and compressive properties of basalt/nylon-epoxy intra-ply hybrid composites are presented. The effect of nylon/basalt fiber content in woven fabric is studied in detail. In addition, after failure visual inspection and SEM analysis were used to determine the type of damage for tested specimens.

Table 1. Physical and mechanical properties of fibers and matrix

Properties	Basalt	Nylon 6	Epoxy
Density (*kg/m*$^{-3}$)	2700	1250	1110
Tensile modulus (*GPa*)	85	2.45	2.73
Tensile strength (*MPa*)	1800	1000	75
Strain at break (%)	2	20.5	2

2. EXPERIMENTAL PROCEDURE

2. 1. Material and Specimen Preparation

The fabric used for these intra-ply hybrid composites is a plain type of basalt and nylon 6 fibers. The basalt fiber was supplied by Hengdian Group Shanghai Russia & Gold Basalt Fiber Co. (China) in the form of 800 Tex, and 360 filament yarn. The nylon fiber was supplied by Junma Tyre Cord Co. (China) in the form of 365 Tex, 360 filament yarn. These fibers were supplied with a suitable sizing for epoxy resin. The matrix resin is a ML-506 epoxy resin supplied by Mokarrar Co. (Iran). HA11 was added to the matrix resin as the hardener. The physical properties of basalt fiber, nylon fiber and epoxy resin are given in Table 1.

All fabrics were manufactured in the Textile Engineering Department of Amirkabir University (Iran) in the form of both pure and intra-ply hybrid fabrics with a rapier loom. Five different types of fabric were produced, namely, a pure basalt fabric, a pure nylon fabric and three hybrid basalt/nylon fabrics with different volume percentages of nylon (25%, 33.3%, 50%). For hybrid fabrics, the percentage of nylon or basalt was equal in the warp and weft directions. The fabric counts in the warp and weft directions were 5 ends/cm and 5 picks/cm, for pure and

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Table 2. Composition of the various plain weave fabrics used for composite manufacturing

Type of fabric	Fabric code	Mass per unit area (kg/m^{-2})	Density (kg/m^{-3})	Fiber type		Fiber distribution (Vol. %)			
				Warp	Weft	Warp		Weft	
						Basalt	Nylon	Basalt	Nylon
Homogeneous basalt	100B	0.795	2700	Basalt		50	0	50	0
Basalt/nylon(75/25)	75B25N	0.743	2320	Basalt & Nylon		37.5	12.5	37.5	12.5
Basalt/nylon(66/33)	66B33N	0.697	2180	Basalt & Nylon		33.3	16.6	33.3	16.6
Basalt/nylon(50/50)	50B50N	0.628	1950	Basalt & Nylon		25	25	25	25
Homogeneous nylon	100N	0.411	1250	Nylon		0	50	0	50

hybrid samples. More details about the composition of each fabric are reported in Table 2. Fabrics were coded by using the percentage of basalt and nylon. For example, sample 66B33N has 66% basalt and 33% nylon in the warp and weft direction.

All composites were made by the hand lay-up method at the Iran Composites Institute (Iran). Composites consisted of four-ply laminates prepared by impregnating each fabric with epoxy resin by means of a hand roller. In Fig. 1 composites are coded according to the fabric codes. Two types of laminates were obtained: intra-ply hybrids (laminates b, c, d) and pure types (laminates a, e). Composite plates were laminated with the cross-ply stacking sequence [(0,90),(90,0)]s. The designations (0/90) represent a single layer of woven fabric with the warp and weft fibers oriented at the zero alignment. The laminates were prepared in the form of square plates (300 × 300 mm^2) and the specimens were then cut from the laminates by using an air-cooled diamond saw. The average thickness, fiber volume fraction, density and void

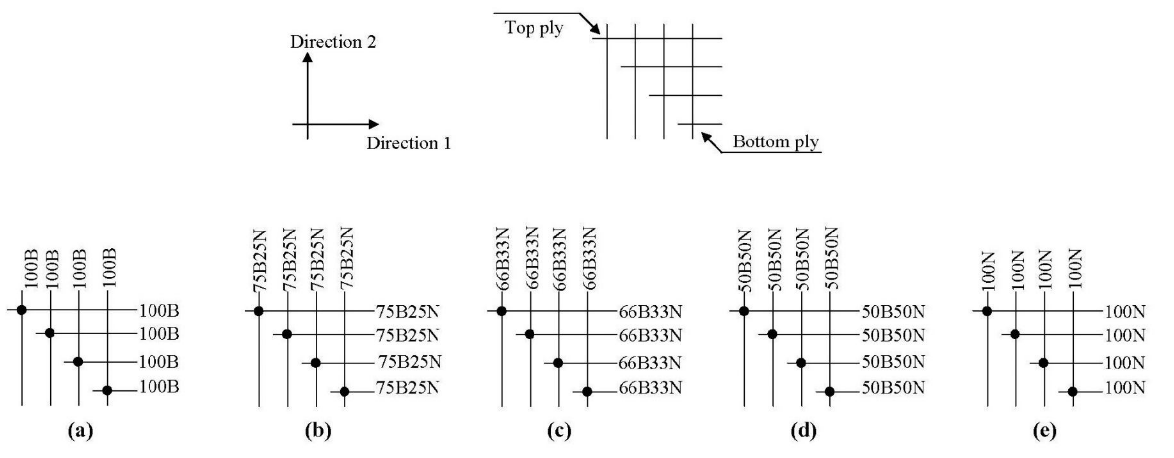

Fig. 1. Stacking sequences of composite laminates: (a) 100B, (b) 75B25N, (c) 66B33N, (d) 50B50N, (e) 100N

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Table 3. Thickness, fiber volume fraction, density and void content for the various laminates

Laminate code	Thickness (mm)	$v_{f\,(\%)}$	ρ_{th} (kg.m^{-3})	ρ_{exp} (kgm^{-3})	Void content (%)
100B	3.11± 0.02	56	1840	1830	0.54
75B25N	3.00± 0.07	63	1750	1720	1.71
66B33N	3.24± 0.05	62	1650	1610	2.42
50B50N	3.62± 0.11	49	1380	1360	1.45
100N	3.21± 0.03	66	1160	1150	0.86

content for the laminates are reported in Table 3.

2. 2. Mechanical Tests

All tests were performed in the Department of Mechanical Engineering of Bologna University, Italy. The method for mechanical testing was based on American Society for Testing Material (ASTM) standards: ASTM D.3039 [21] for tension test and ASTM D.3410 [22] for compression test. The tests were carried out on rectangular specimens with a standard dimension (250mm×25mm for tension test and 150 mm×25 mm for compression test), along the loading directions 1 in Fig. 1. For calculating the tensile and compressive modulus and Poisson's ratio, strain gauges were mounted on one surface of each specimen based on ASTM standards.

All samples were tested by using an Instron 8033 tester equipped with a 250 kN load cell (Fig. 2a). For each test, the special fixture was used on this instrument (Fig. 2b-c). The distance between the grips was fixed at 100 mm and 20 mm for tensile and compressive tests, respectively. All tensile and compressive measurements were carried out at a constant cross-head speed of 2 mm/min on at least five specimens.

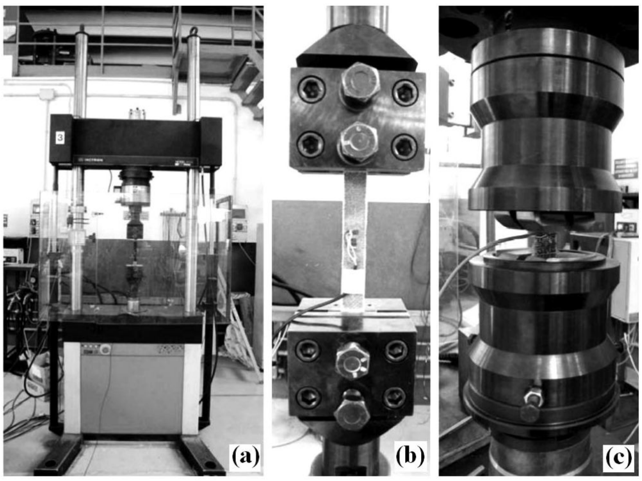

Fig. 2. Instron 8033 tester (a) overall view of the machine (b) tension fixture, (c) compression fixture.

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During the test, a data acquisition system recorded the force versus displacement history. From the basic force–displacement information, important parameters such as stress and strain were calculated. The Poisson's ratio and modulus of each type of laminate were calculated by using strain gauge information.

2. 3. Scanning Electron Microscopy (SEM)

Fractography of the failure surfaces of the composite samples was examined by a scanning electron microscope, Philips model XL30. The fractured portions of the samples were cut and the SEM micrographs were taken. A uniform coating of the gold was given to the samples in order to make the surface conductive, and the samples were then examined under the scanning electron microscope. The accelerating voltage was 17 kV. Micrographs of the fractured portions were taken under different magnifications. Tensile and compressive fractograph of the composites were taken to study the fracture mechanisms and interface adhesion of the composites.

2. 4. Statistical Analysis

One-way analysis of variance (ANOVA) was used to compare the strength and modulus between the five pure and hybrid laminates. A P-value <0.05 was considered significant.

3. RESULTS AND DISCUSSION

3. 1. Tensile Properties

Typical stress–strain curves, obtained for pure and hybrid composites, reported in Fig. 3, are characterized by a monotonic load increase up to complete rupture. It can be seen how the stress–strain behavior is strongly affected by the nylon/basalt fiber content. The pure specimens (100B and 100N) were loaded uni-axially until immediate rupture occurred. Intra-ply hybrid composites showed a more complex tensile behavior, characterized by a progressive failure of the various fibers. For hybrid specimens, in which both basalt and nylon fiber are simultaneously present along the loading direction (75B25N, 66B33N, and 50B50N), two subsequent load drops could be detected: the first load drop was associated with the failure of the basalt fiber and the second one corresponded to the failure of the nylon fiber. These results are in agreement to what was found by Pegoretti and co-workers [15] who reported that the stress-strain curves of the intra-ply hybrid composite showed a step by step decrease of the load while the pure composite showed a sudden drop of the load.

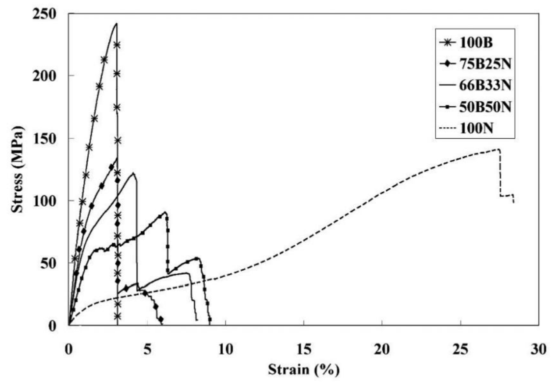

Fig. 3. Stress-strain behavior of various composites obtained from tensile tests

The 100N and hybrid samples showed a pronounced 'knee', located between 1.2 and 1.6 % strain, which is associated with the peculiar yielding behavior of the nylon fiber used for composite manufacture, as confirmed by tensile tests performed on single nylon fiber [23]. The stress–strain slope change displayed by the basalt pure sample, at a strain level of about 2.0 % (which is also detectable in the other samples especially in 50B50N), was probably related to the occurrence of matrix damage, as can be hypothesized on the basis of the pure matrix break strain also reported in Table 1.

From the results, the 100B laminate shows the highest maximum strength, steep initial slope, and low strain at break. These results are attributed to the low elongation and high modulus of the basalt fiber. On the contrary, the 100N laminate exhibits slow load rise and high strain at break. These features suggest that the composite bears the applied load up to higher strain, and failure occurs in a ductile manner because of the

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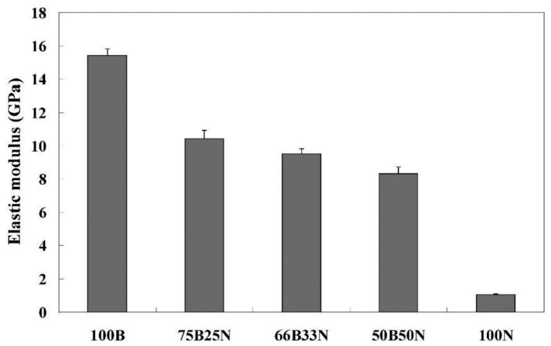

Fig. 4. Elastic modulus of samples with different contents of basalt and nylon

high elongation of the nylon fiber [12, 13, 23]. The hybrid composites have a lower maximum strength than the pure ones. In these composites, the basalt and nylon fiber cannot reach their maximum strength at the same time and the progressive failure of the various fibers therefore occurred. In hybrid composites, by increasing the nylon/basalt fiber ratio the maximum strength decreases. It is interesting to observe that, by increasing the nylon content, the stress and strain at break (the second load drop) increased, accounting for an improved tensile energy to break. In these composites, increasing the content of nylon causes the laminates to become less stiff and resists the tensile load in a ductile manner [20]. Fig. 4 shows the elastic modulus as a function of nylon/basalt fiber content. It can be seen that by increasing of nylon/basalt fiber ratio the elastic modulus decreases.

The tensile experimental data obtained for various composites are summarized in Table 4, while Table 5 reports the specific tensile data, i.e., values normalized to the material density. By looking at the specific properties, it is clear that most hybrid composites (66B33N and 50B50N) have specific tensile strain energy to break values which are comparable to, or higher than those of pure basalt composites. Hybrid composites also have a higher specific elastic modulus than pure nylon composites.

Scanning electron micrographs of the tensile fractured surfaces of the composites were taken in order to understand the fracture mechanism. Fig. 5 shows SEM studies on the failure surface of pure and intra-ply hybrid composites. Extensive nylon fiber pullout was observed not only in the pure nylon composite (Fig. 5(a)) but also in the hybrid composites (Fig. 5(b)-(c)) while basalt fiber fractures were observed in the pure basalt composite (Fig. 5(e)) and in the hybrid composites (Fig. 5(c)–(d)). The weak interfacial adhesion between the nylon fibers and epoxy resin leads to the pullout of fibers from the matrix while the better adhesion between the basalt fibers and epoxy matrix resulted in fiber fracture. Nylon fiber/matrix interfacial failure is evident from Fig. 5(a)-(b). The existence of epoxy matrix adhered to the surface of the basalt

Table 4. Experimental data obtained from the uniaxial tensile tests on the various composites

Sample	Elastic modulus (*GPa*)	Maximum stress (*MPa*)	Strain at maximum stress (%)	Poisson ratio 12	Strain at break (%)	Strain energy to break (*J.m*$^{-3}$)
100B	15.42± 0.41	244±5	3.2± 0.1	0.16	3.2± 0.1	483±9
75B25N	10.43± 0.51	128±8	3.3± 0.1	0.15	4.4± 0.1	334±14
66B33N	9.52± 0.37	122±6	4.3± 0.2	0.16	7.4± 0.1	467±12
50B50N	8.32± 0.42	85±4	5.2± 0.2	0.23	8.5± 0.2	463±19
100N	1.05± 0.05	135±4	26.9± 0.7	0.27	26.9± 0.5	1766±23

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fibers indicates perfect adhesion as shown in the scanning electron micrographs of the tensile fractured surfaces of the composites (Fig. 5(d)-(e)).

Table 5. Specific tensile data obtained for the various composites

Sample	Specific elastic modulus ($MPa.\ m^3.kg^{-1}$)	Specific maximum stress ($kPa.\ m^3.kg^{-1}$)	Specific energy to break ($mJ.kg^{-1}$)
100B	8.91± 0.22	141± 2.8	279±5
75B25N	6.24± 0.29	77± 4.7	200± 5
66B33N	5.87± 0.18	76± 3.7	288± 6
50B50N	6.07± 0.29	62± 2.9	337± 14
100N	0.91± 0.04	116± 3.4	1509± 59

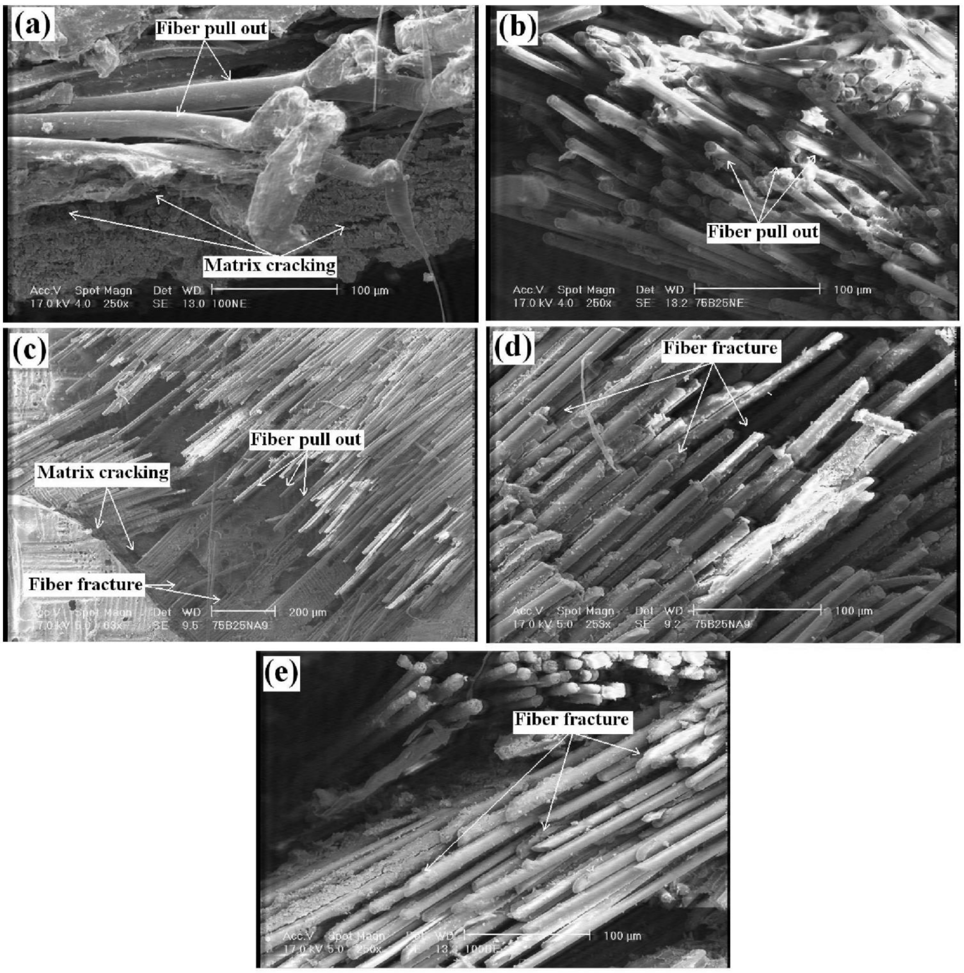

Fig. 5. Scanning electron micrographs of tensile fractured surfaces of basalt/nylon composites; (a) 100N, (b)-(d) 75B25N, (e) 100B

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3. 2. Compressive Properties

Fig. 6 shows SEM micrographs of fracture surfaces of different composites after the compression test. In this figure, it can be seen how the type of damage in tested specimens is strongly affected by the nylon/basalt fiber content.

Fig. 7 shows the stress-strain behavior of pure and hybrid composites obtained from instrumented compression testing. This figure shows the various changes in failure mechanism during compression event. It can be seen that the pure basalt specimen are loaded uni-axially until catastrophic and complete rupture occurred. In this specimen the load drop is associated with the failure of the matrix and basalt fiber (see Fig. 6(a)). The other specimens show a progressive failure. The pure nylon specimen failed in a ductile manner like plastic material. The failure can be related to the matrix breakage in composites. In this composite the failure of nylon did not happen and this fiber was bent in the damage area (See Fig. 6(b)). The hybrid composites show a response between 100B and 100N laminates. For these specimens, load drop is associated with the failure of the matrix and basalt fiber (See Fig. 6(c)) and the nylon yarns prevented catastrophic and complete rupture (See Fig. 6(d)).

The compressive experimental data obtained for various composites are summarized in Table 6. This table also reports the specific compressive data, i.e. values normalized to the material density. The results indicate that the 100B laminate shows the highest compressive strength and the least failure strain. On the contrary, the 100N laminate exhibits the least compressive strength and the highest failure strain. In hybrid composites, by increasing the nylon/basalt fiber ratio there is no trend in compressive strength and failure strain. In these composites the 50B50N has the highest compressive strength. This can be

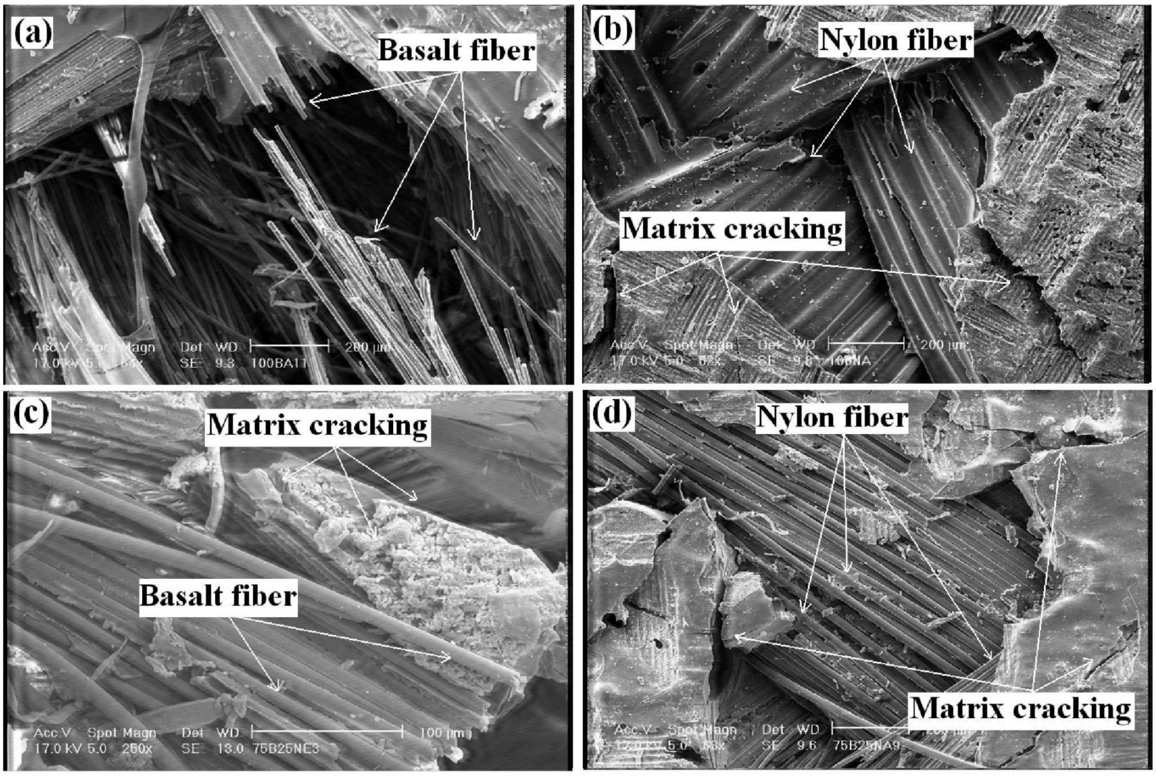

Fig. 6. Scanning electron micrographs of compressive fractured surfaces of basalt/nylon composites; (a) 100B, (b) 100N, (c)-(d) 75B25N

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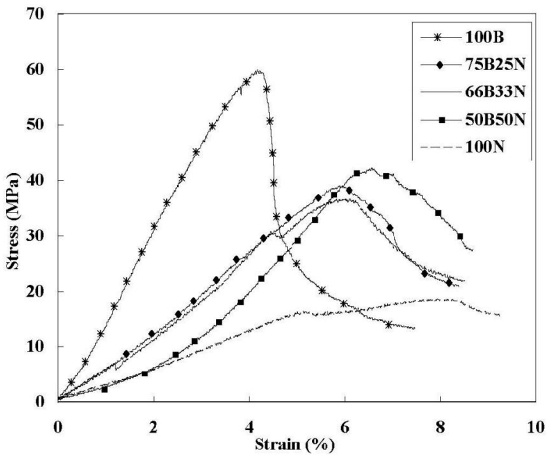

Fig. 7. Stress-strain behavior of various composites obtained from compressive tests

attributed to the greater thickness of this specimen (Table 3).

The results (see Table 6) show that by increasing the nylon/basalt fiber ratio the compressive modulus decreased. The compressive modulus of 100B is sevenfold that of 100N laminates. By looking at the specific properties, it is clear that some hybrid composites (75B25N) have specific compressive modulus values which are comparable to the pure basalt composites. In addition, the hybrid composites have higher specific compressive modulus and failure strength than the pure nylon composites.

During the compression test of some specimens, the discernible failure occurred in constrained regions, such as the tabbed region. In these specimens, premature failure following the end crushing occurred. According to the ASTM D-3410 [22], the results of these specimens are not acceptable.

The initiation and development of failure mechanisms cannot be observed easily, since the matrix is relatively brittle and fracture is almost instantaneous and catastrophic in some specimens. Failure mechanisms were recorded only after the test (after failure) by means of SEM micrographs and close-up photos through the thickness of the specimens. Fig. 8 shows the photos of compressive damage through the thickness of pure and hybrid laminates. According to ASTM D-3410, typical compression failure for pure basalt laminate was through-thickness and transverse shear modes (Fig. 8(a, b)). In hybrid samples, long-splitting was the most important failure mode (Fig. 8(e, f)). In addition, in hybrid composites through-thickness and transverse shear modes were

Table 6. Experimental data obtained from the compressive tests on the various composites

Sample	Compressive modulus (*GPa*)	Maximum stress (*MPa*)	Strain at maximum stress (%)	Specific compressive modulus ($MPa.\ m^3.kg^{-1}$)	Specific maximum stress ($kPa.\ m^3.kg^{-1}$)
100B	14.72± 0.31	65±3	4.1± 0.2	8.51± 0.17	38± 1.7
75B25N	12.16± 0.75	38±1	6.0± 0.2	7.28± 0.42	23± 0.6
66B33N	8.20± 0.43	37±2	6.2± 0.3	5.06± 0.24	23± 1.2
50B50N	7.40± 0.42	43±1	6.7± 0.4	5.40± 0.29	31± 0.7
100N	2.11± 0.11	19±1	8.2± 0.3	1.80± 0.08	17± 0.8

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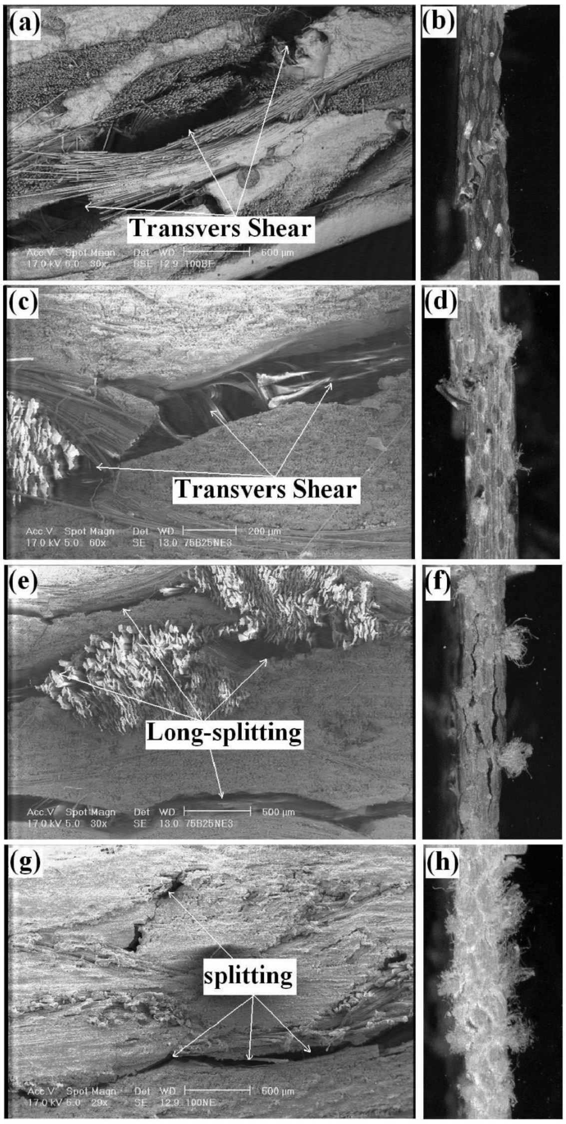

Fig. 8. Schematic of damage in composite specimens after compression; Column 1: SEM micrographs, Column 2: close-up photo, (a, b) 100B, (c-f) 75B25N, (g, h) 100N

observed (Fig. 8(c, d)). After the compression test there was a little splitting through the thickness of pure nylon laminate (Fig. 8 (g, h)). In high nylon content specimens, especially in 100N, the nylon yarns help the damaged basalt yarns and after compression the specimen returns to its original shape before failure. The integrity of these composites after compression was therefore maintained.

4. CONCLUSIONS

In this study, the tensile and compressive properties of basalt/nylon intra-ply hybrid composites were investigated as a function of nylon fiber content. The following conclusions can be drawn from this work.

- The pure basalt laminate shows the highest tensile and compressive strength. The pure nylon laminate exhibits the least compressive strength and the highest tensile and compressive failure strain.
- The hybrid composites have a lower tensile strength than the pure ones. In these composites, by increasing the nylon/basalt fiber ratio the tensile strength decreased.
- In hybrid composites, by increasing the nylon/basalt fiber ratio there is no trend in compressive strength.
- By increasing the nylon/basalt fiber ratio the tensile and compressive modulus decreased.
- In tensile and compression conditions, hybridization can prevent catastrophic and complete failure. In hybrid composites, the basalt and nylon fibers cannot reach their maximum strength at the same time and the progressive failure of the various fibers therefore occurred.
- For high nylon content specimens, nylon yarns help the damaged basalt yarns and after compression the specimen returns to its original shape before failure. The integrity of these composites after compression was therefore maintained.
- With a proper choice of fiber content, the basalt/nylon hybrid composites can achieve mechanical properties comparable with, or better than the pure ones.

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