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Experimental investigations on the thermo-mechanical properties of carbon-basalt-aramid/epoxy and glass-basalt-aramid/epoxy hybrid interply composites under different aging environments

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Abstract. In this study, Carbon-Basalt-Aramid (C-B-A) and Glass-Basalt-Aramid (G-B-A) samples were produced, and their thermal expansion coefficient (α), glass-transition temperature (Tg), and dimension change properties were investigated. In the study, thermo-mechanical properties of hybrid composites with and without 12 h and 48 h aging processes were determined. As a result, the properties obtained according to the results of TMA analysis of both hybrid composites with the aging process changed significantly.

1. Introduction

High-performance fiber-reinforced composites offer excellent strength and stiffness properties, but their relatively high material and manufacturing cost, and their brittle, catastrophic failure without sufficient warning, limit their use in high-volume applications such as mass-produced automotive and construction. To expand their use, the development of high-performance ductile or pseudo-ductile composites with safe failure mechanisms similar to metals, with detectable warning and a wide margin before final failure, is of significant interest. However, adding ductility to composite materials is challenging as both traditional constituents of high-performance long fiber-reinforced thermoset polymer matrix composites are brittle [1-3]. Researchers have investigated various approaches to improve the ductility of composites such as modified matrix systems, new ductile fibers, and modified composite architecture [4-5].

A common one of these approaches is with out-of-plane fluctuation, which can create extra stress before breaking by creating additional tension through the realignment of conventional laminated composites or allowing the fibers to be reorientated [6-9]. Thus, the fracture is delayed and nonlinearity can be created through controlled damage before eventual failure. The other can be accomplished by hybridizing commercially available unidirectional plies so that they can be used to maintain a high initial modulus and potentially cause a cascading failure, but this can often produce undesirable large load drops when lower strain fibers break [10-11]. Layered hybrid [12-13] and mixed hybrid [14-15] structures have been investigated to improve the brittleness of single fiber composites. Then, hybrid composites with more than one type of single-phase reinforcement gained importance due to the freedom of adaptation of single fiber type composites according to needs. Thus, high strength can be achieved with less weight and cost for extensive engineering applications.

Some of the recent research on these composites, called hybrids, is as follows:

Czel et al. [16] studied the optimum hybrid configuration of carbon/glass reinforced hybrid composites and emphasized that the increase in the number of carbon layers increases the ductility of the material. Wu et al. [17] studied the effects of hybridization on the bending performance of carbon/glass interlayer and interlayer composites and emphasized that interlayer hybrid composites containing less carbon fiber exhibit excellent bending behavior. Bhagwat et al. [18] obtained Young's modulus, tensile strength and compressive strength, and Poisson's ratio from tensile and compression tests of hybrid glass/carbon composites. Chelliah et al. [19] characterized various failure modes in glass, carbon hybrid composite laminates under uniaxial tensile loading with acoustic emission (AE) monitoring and presented individual failure modes and failure times. Aslan et al. [20] studied the tribological and mechanical performance of sisal-filled waste carbon and glass fiber hybrid composites. Melo et al. [21] studied the effect of Portland cement admixture on hybrid glass fiber-reinforced composites based on full factorial design. Ramlee et al. [22] studied the physical and morphological and mechanical properties of natural fiber-reinforced phenolic hybrid composites.

In recent studies, the investigation of mechanical and thermo-mechanical properties under the static and dynamic influence, including fibers other than carbon and glass, has also been the subject of many studies [23-25]. Supian et al. [26] investigated the high impact strength of a filament wound kenaf/glass hybrid composite energy absorption tube under medium velocity impact load conditions. They emphasized that the energy absorption value of the hybrid sample with high kenaf fiber fraction mass increased significantly. Wahab et al. [27] discussed the conceptual design of a glass/renewable natural fiber reinforced polymer hybrid composite motorcycle side cladding. They stated that the glass/coconut fiber reinforced polypropylene hybrid composite increases weight but reduces thickness due to higher density.

Sahu et al. [28] numerically investigated the time-dependent displacement behavior of glass-Carbon-Kevlar fiber-reinforced hybrid shell panels under thermo-mechanical loading. Charvani et al. [29] performed impact and Thermogravimetric analysis of the hybrid composite produced using carbon and Aramid fibers by adding alumina nanoparticles to the binder resin matrix. They observed that the thermal stability increased with nanoparticle loading and stated that the use of both fibers together increased the impact strength. Wu et al. [30] investigated the longitudinal and transverse shear properties of 3D braided hybrid composites using aramid and carbon fibers. They stated that the transverse shear property of the hybrid braided structure is superior to the longitudinal shear and showed the failure modes. Protchenko et al. [31] investigated the tensile and shear strength of basalt/carbon fibers and hybrid composite rods. They emphasized that hybrid rods have better tensile and shear strength than basalt fiber rods.

Yashas Gowda et al. [32] studied the effect of stacking order on the mechanical and thermal properties of flax, kevlar, carbon, and carbon-kevlar hybrid fiber composites. They investigated the thermal behavior by performing tensile, bending, interlayer shear, and impact tests for four-layer composite laminates with different stacking orders. Shishevan et al. [33] studied the mechanical and thermal properties of carbon fiber composites. They performed the different test to determine the tensile and bending behaviors. They determined that the viscoelastic properties of carbon fibers were significantly affected by the increase in thermal energy.

Grimurugan et al. [34] studied the thermal properties of carbon and kevlar-reinforced hybrid material. They determined the materials' thermomechanical properties, hardness, impact strength, bending strength, and thermal conductivity. Mishra et al. [35] investigated the mechanical and thermomechanical properties of basalt nanoparticle basalt/basalt reinforced hybrid composite material and basalt/jute reinforced hybrid composite material. For thermal stability, they performed different tests and emphasized that the basalt/basalt material with basalt nanoparticles had better mechanical and thermal properties.

Karacor and Ozcanlı [36] investigated the thermal and mechanical properties of basalt/carbon hybrid and basalt/aramid hybrid structures. They emphasized that the basalt/carbon hybrid is good in terms of tensile and microhardness. They also stated that the carbon fiber hybridization to basalt fabric greatly improves the deformation resistance and heat resistance of the materials compared to the aramid fabric hybridization process.

Raj et al. [37] fabricated the glass, basalt, aramid, and carbon hybrid composite with different interlayer configurations and investigated its natural frequency and damping behavior and stated that hybrid composites with carbon-glass-aramid fibers have the best damping properties.

Pai et al. [38] investigated the mechanical properties of basalt and aramid fiber hybrid composites under three different aging conditions and emphasized that moisture absorption has a negative effect. They showed that matrix segregation, matrix cracks, and interfacial bond rupture occur under the aging effect.

In this study, thermo-mechanical properties of carbon-basalt-aramid/epoxy and glass-basalt-aramid/epoxy hybrid composite materials such as α, Tg, and dimensional change properties under different aging conditions will be investigated. These hybrid composites to be produced with three different reinforcement elements have not been found in the detailed literature, and in this respect, our study will create an innovation.

2. Experimental process

In this study, the selection of reinforcement elements was made by considering the properties we want to achieve. Glass fiber (200 gr/m^2) with high strength and thermal insulation properties; carbon fiber (200 gr/m^2) for lightness, good thermal and electrical conductivity; basalt fiber (210 gr/m^2) for thermal strength; Aramid fiber (200 gr/m^2) was chosen for high friction and abrasion resistance. Hexion MGS® L 326 high-temperature system was used as resin and 770-NC was used as a mold release agent.

2.1 Hybrid interply composite sample production

Two hybrid composites were produced for this study. The first one is reinforced with G-B-A fiber and the second one is reinforced with C-B-A fiber. The samples are 3mm in total thickness and 500x500 mm in size. Each of the samples was produced using 16 fibers in 9 hours, including curing, and these fibers were sorted according to their manufacturability. The fibers placed in each layer of the plates in production were arranged by hand laying method and epoxy was applied and laminated with a deaeration roller. Between each fiber stack, 10 minutes was allowed for the gel time of the epoxy. After the epoxy process applied to each floor was finished, it was pressed between 120-150°C for 6 hours in order for the material to become a plate.

In this study, the thermo-mechanical behavior of the material was investigated by determining the α, Tg, and dimensional change properties under different temperatures by applying the aging process to the samples produced. The fiber array of two different hybrid composite samples with three reinforcement elements is shown in Figure 1.

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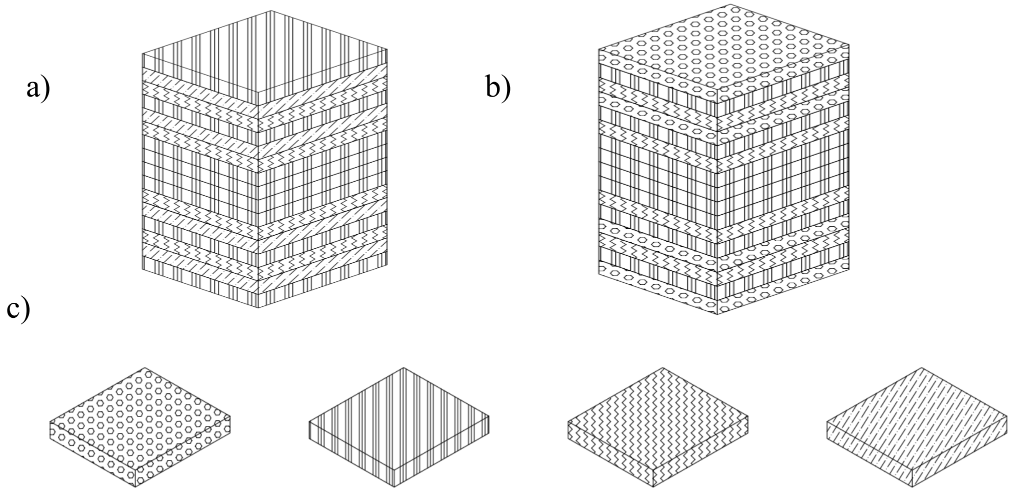


Figure 1. Fiber sequence of hybrid composite material a) G-B-A hybrid composite, b) C-B-A hybrid interply composite, c) fibers in samples (carbon, basalt, aramid, glass fibers, from left to right, respectively)

2.2 Aging process

12 and 48 h UV aging of hybrid composite samples were performed with PN-EN-ISO 4892-3 standard / fluorescent UV lamps and ATLAS ultraviolet TEST device. The aging process was carried out in an aging chamber with 8 fluorescent UV lamps (UVA 340, UVB 313, UVA 351). This instrument is designed to test resistance to photo-oxidation, i.e., ultraviolet A and ultraviolet B, the most destructive range to UV radiation. According to this test standard, it is designed to simulate the wear effects that occur when materials are exposed to global solar radiation or solar radiation in real end-user environments. The samples were cut in dimensions of 10mmx10mmx3mm before being tested. Two different hybrid samples were aged for 12 and 48 h (Figure 2). In the aging process, the samples were exposed to UVA -340 lamps and a radiation intensity of 0.75W/m². In the 12 h aging process, the samples were exposed to irradiation at 8 h and 50 °C, then left to rest for 3 h, 45 min, and below 50 degrees. After the listening process, 15 minutes of spraying was done, and 12 hours were completed. For 48 h aging, similar processes to the hybrid composite material were applied at different times.

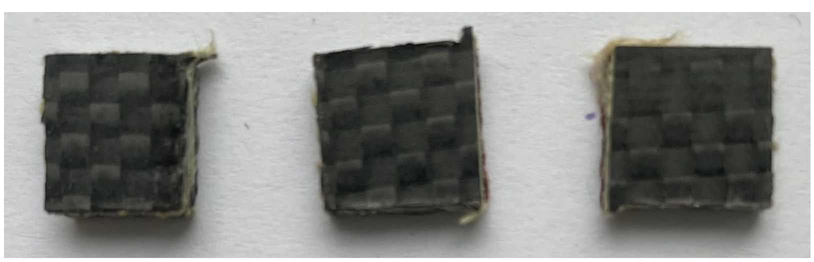


Figure 2. C-B-A reinforced hybrid composite specimens from left to right, respectively; no aging process was applied, 12 h aging process was applied and 48 h aging process was applied.

2.3 Thermo-mechanical analysis (TMA)

TMA test in expansion mode with TA Instruments TMA Q400 device was performed by increasing the temperature with 5ºC/min heating rate under 0.02 N load in the range of -30 ºC to 120 ºC according to ASTM E831 standard. This device allows us to determine the α, Tg, and dimensional change properties that is, the thermo-mechanical behavior of the samples under a certain load, according to the parameters determined at different temperatures.

In these tests, the determination of α and Tg. TMA test was performed for 6 samples (no aging process, 12 h aging process, and 48 h aging process) for 2 different hybrid composites.

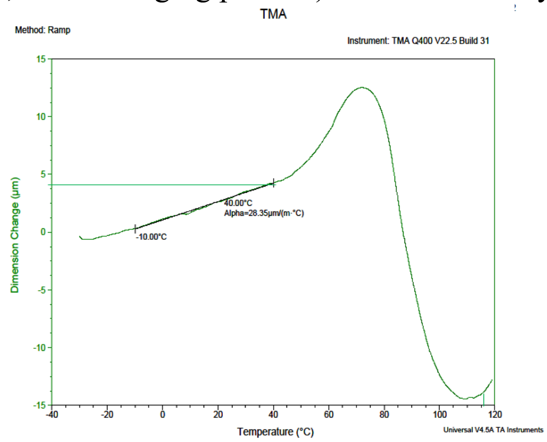
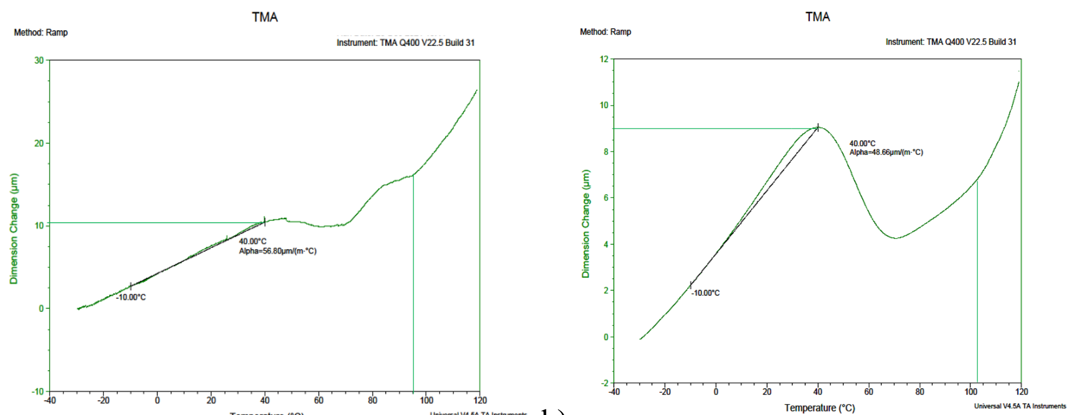


Figure 3. TMA result of C-B-A reinforced hybrid composite material without aging process.

The TMA results for the C-B-A hybrid composite are shown in Figure 3 for the sample without the aging process. Here the dimensional change was measured as 4.2 µm, α=28.35 µm/(m°C), and Tg=115 °C.



a) b)

Figure 4. TMA result of C-B-A reinforced hybrid composite material that has been aged for a) 12 h b) 48 h.

The TMA results for the C-B-A hybrid composite sample with the aging process applied for 12 h are shown in Figure 4-a). Here the dimensional change was measured as 10.3 µm, α=56.80 µm/(m°C), and Tg= 95°C. TMA result of C-B-A reinforced hybrid composite material that has been aged for 48 h. The TMA results for the C-B-A hybrid composite sample with the aging process applied for 48 h are shown in Figure 4-b). Here the dimensional change was measured as 9 µm, α=48.66 µm/(m°C), and Tg=102.5°C. The Tg for the C-B-A hybrid composite without the aging process, 12 h aging process, and 48 h aging process applied for the samples, respectively, is 115 °C, 95 °C, and 102.5 °C, this value decreases when the aging process is performed and decreases when the processing time is increased. Similarly, the expansion coefficients of the samples vary as α=28.35 µm/(m°C), α=56.80 µm/(m°C), and α=48.66 µm/(m°C), respectively. Dimensional change amounts are respectively; 4.2 µm, 10.3 µm, and 9 µm. In both values, depending on the aging application time, first an increase and then a decrease occurs. This shows that the thermo-mechanical properties of the C-B-A reinforced hybrid composite are significantly affected by aging.

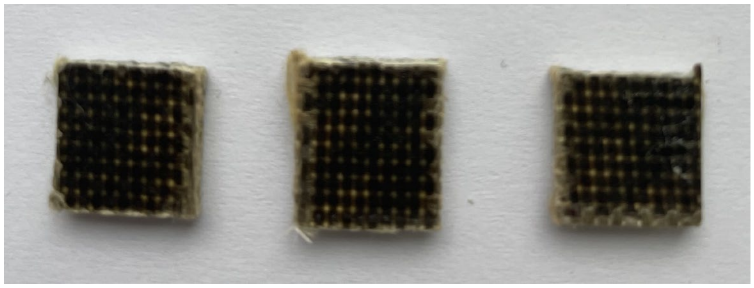


Figure 5. G-B-A reinforced hybrid composite specimens from left to right, respectively; no aging process was applied, 12 hours aging process was applied and 48 hours aging process was applied.

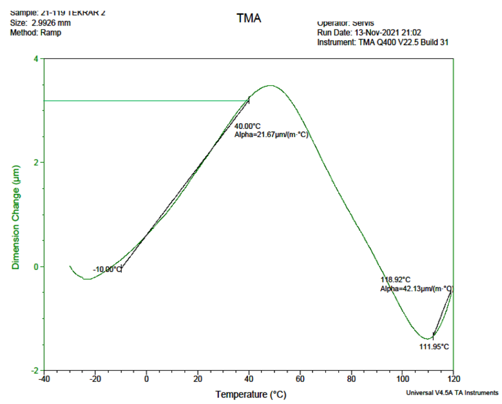
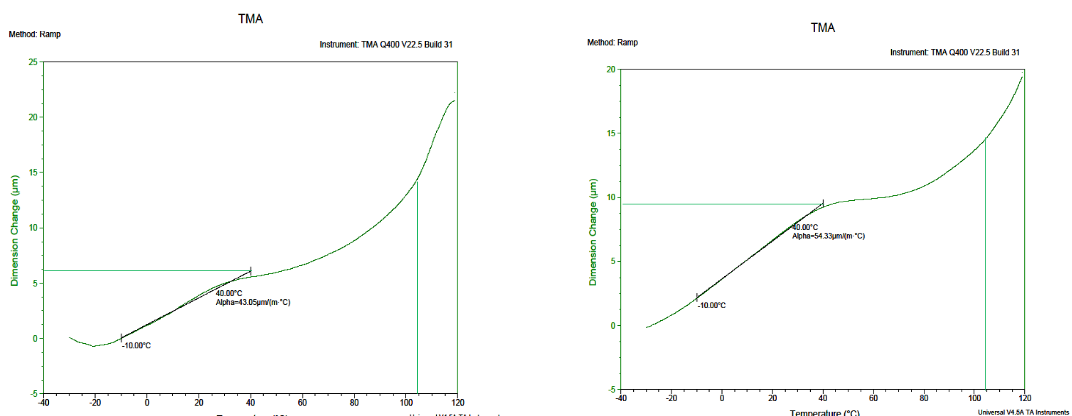


Figure 6. TMA result of G-B-A reinforced hybrid composite material without aging process.

The TMA results for the G-B-A hybrid composite are shown in Figure 6 for the sample without the aging process. Here the dimensional change was measured as 3.2 µm, α=21.67 µm/(m°C), and Tg=111.95 °C.



a) b)

Figure 7. TMA result of G-B-A reinforced hybrid composite material that has been aged for a) 12 h b) 48 h.

The TMA results for the G-B-A hybrid composite sample with the aging process applied for 12 h are shown in Figure 7-a. Here the dimensional change was measured as 6.25 µm, α=43.05 µm/(m°C), and the Tg=104.85°C. The TMA results for the G-B-A hybrid composite sample with the aging process applied for 48 h are shown in Figure 7-b. Here the dimensional change was measured as 9.4 µm, α=54.33 µm/(m°C), and Tg=105°C. The Tg for the G-B-A hybrid composite without the aging process, 12 h aging process, and 48 h aging process applied for the samples, respectively, is 111.95 °C, 104.85 °C, and 105 °C, this value increases when the aging process is performed. Similarly, the expansion coefficients of the samples vary as α=21.67 μm/(m°C), α=43.05 μm/(m°C), and α=54.33 μm/(m°C), respectively. Dimensional change amounts are respectively; 3.2 μm, 6.25 μm, and 9.4 μm. Both values increase depending on the aging application time. This shows that the thermo-mechanical properties of the G-B-A reinforced hybrid composite are significantly affected by aging.

Table 1. TMA test results for two hybrid composites

Aging process time [h]	Sample	Dimensional change [μm]	α [μm/(m°C),]	Tg [°C]
-	C-B-A	4.2	28.35	115
-	G-B-A	3.2	21.67	111.95
12	C-B-A	10.3	56.80	95
48	C-B-A	9	48.66	102.5
12	G-B-A	6.25	43.05	104.85
48	G-B-A	9.4	54.33	105

It is seen that the thermal properties of the G-B-A reinforced hybrid composite material with and without the aging process are more affected than the C-B-A reinforced hybrid composite material (Table 1). According to these results, the high-density fragility of glass fiber in G-B-A reinforced composite, combined with low thermal properties, high strength of aramid fiber, and high thermal resistance properties of basalt fiber, strengthened the weaknesses of glass fiber.

3. Result and conclusion

In this study, two different hybrid composite samples with three reinforcements were produced and the α, Tg, and dimensional change amounts of the composites were determined by TMA. In addition, the change in these properties was investigated by applying the aging process to both composite samples.

The dimensional change and α of the aged C-B-A hybrid composite material increased by an average of 2.3 times and 1.85 times, respectively, while the Tg decreased by an average of 0.855 times compared to the unaged condition. The dimensional change and α of the aged G-B-A hybrid composite material increased by an average of 2.44 times and 2.24 times, respectively, while the Tg decreased by an average of 0.93 times compared to the unaged condition. According to the results of this study, it has been shown that the aging process has a significant effect on the thermo-mechanical results presented and the effectiveness of the selection of each reinforcement element of the hybrid composite on these properties.

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