Structural and mechanical behaviour of glass fibre reinforced polyester composites

DOI: 10.35530/IT.076.04.2024198

MEHMET KARAHAN AMINODDIN HAJI

ABSTRACT – REZUMAT

Structural and mechanical behaviour of glass fibre reinforced polyester composites

In this research, an investigation was conducted on the mechanical properties of polyester resin composites produced by three different methods: hand lay-up, Resin Transfer Moulding (RTM) and Sheet Moulding Compound (SMC) methods, reinforced with randomly distributed discontinuous and continuous glass fibre mat. Firstly, tensile strength and elastic module were found to determine the composite plates' mechanical properties. Impact strength was determined by the Charpy impact test. To determine the deformation on the materials after impact, the samples exposed to low-speed drop weight were applied the 3-point bending test and their strength losses were determined. It was determined that the increase in fibre volume fractions increased the impact strength of the composite materials. However, the use of filler materials in composite structures decreased the mechanical properties and impact strength of composites.

Keywords: *polymer composite, SMC, RTM, hand lay-up, impact strength*

Comportamentul structural și mecanic al compozitelor poliesterice ranforsate cu fibre de sticlă

În această lucrare, a fost efectuată o investigație asupra proprietăților mecanice ale compozitelor din rășină poliesterică produse prin trei metode diferite: aplicare manuală, turnare prin transfer de rășină (RTM) și metode de turnare în foi (SMC), armate cu văl de fibre de sticlă discontinuu și continuu, distribuit aleatoriu. În primul rând, s-au determinat rezistența la tracțiune și modulul de elasticitate pentru a analiza proprietățile mecanice ale plăcilor compozite. Rezistența la impact a fost determinată prin testul de impact Charpy. Pentru a determina deformarea materialelor după impact, probele expuse la greutatea de cădere la viteză mică au fost supuse testului de încovoiere în 3 puncte și au fost analizate pierderile de rezistență ale acestora. S-a stabilit că creșterea fracțiilor volumice de fibre a majorat rezistența la impact a materialelor compozite. Cu toate acestea, utilizarea materialelor de inserție în structura compozitelor a diminuat proprietățile mecanice și rezistența la impact ale acestora.

Cuvinte-cheie: *compozit polimeric, SMC, RTM, aplicare manuală, rezistență la impact*

INTRODUCTION

Today, the automotive industry is one of the largest and most significant sectors in the world, and it has become a major consumer of engineering materials. Although metallic materials are predominantly used in this sector, the cultural and economic changes in recent years have significantly influenced both material preferences and design choices. The development of polymer composite materials has become an important supportive parameter for this change [1, 2]. Four factors are very important in the widespread use of composite materials in the automotive industry: weight saving, security, product quality, production ease and flexibility [3]. The high energy absorption ability of composite materials makes them more advantageous than classic materials such as aluminium and steel, and because of these properties, their usage has increased in automotive parts that are exposed to collisions [4]. A chassis made of a composite material absorbs 80% more energy than a steel chassis in the case of a collision [5].

The easy moulding property of composites provides several advantages. The production of big structural complex parts as a whole eliminates the necessity of part combining and montage, which allows materials to be produced with higher resistance and lower cost. Moulding processes are easy, and colouring during moulding decreases the production time and cost, and allows more colour options and aesthetic features. As a result, composite materials are being used in the production of outer body parts in the automotive industry [6].

Automotive manufacturers are currently under pressure to produce low-cost automobiles that are resistant to environmental factors, have a high security level, provide very good comfort and equipment, and consume less fuel. Under these circumstances, composite materials are considered to be the most convenient materials that can be used instead of aluminium and steel. The easiest method for establishing lightweight materials without concession from strength is the use of carbon fibre-reinforced composites. However, carbon fibres are expensive for automotive applications. On the other hand, glass fibre has found a very prevalent application area in the automotive industry together with thermoplastic and thermoset resins, due to its high rigidity and low cost [7, 8]. Owing to new developments in production processes and moulding techniques, glass fibre mats are being used in lightweight and high-performance automotive parts [9]. Some important moulding methods in the production of automotive composites are the hand lay-up method, sheet moulding compounds (SMC), bulk moulding compounds (BMC) and resin transfer moulding (RTM). The products produced using these methods are used inside beams, ceiling and bottom panels, exterior body panels, bumpers, and mudguards. While a ready fibre–resin mixture is used in the production of these parts with SMC and BMC methods, discontinuous and continuous fibre mats, woven, knitting, and unidirectional fabrics can be used as reinforcement with other methods such as RTM and hand lay-up [10]. Generally, automotive composites are expected to exhibit high impact strength, high tensile strength, high fatigue resistance, and strength preservation at different temperatures.

Collision resistance is particularly important in automotive parts, and research has generally focused on the impact strengths and mechanical properties of automotive composites. Simunovich et al conducted a comprehensive study on this subject [11]. In this study, the damage behaviour and propagation properties of random glass fibre mat–polyester resin composite materials were determined experimentally, and the damage behaviour of the composite parts was modelled using the DYNA3D simulation program. Santulli et al. [12] investigated the impact strengths in glass fibre–polypropylene thermoplastic composites by the Charpy test. In another study, Piry et al. [13] analysed the impact strengths and damage of glass fibre–polyester resin composites produced by the SMC method. The impact strength when the fibre distribution and fibre volume fraction were changed in the structure was theoretically determined using the EXPRESS simulation program. The loading amounts for initialising a crack and the total energy amounts for the structure to fracture were theoretically calculated, and the results were compared with experimental data. Oldenbo et al. [14] investigated the mechanical properties and fracture toughness of standard and low fibre volume fraction glass fibre–polyester resin SMC composites and found that SMC composites with lower densities are more resistant to small collisions. In a similar study, Gregl et al. [15] found that the Young's modulus was 20% lower when 10% of glass spheres were added to the SMC composition as a filler. Sheu et al. [16] found that 30% weight was saved when glass fibre-vinyl ester composites produced by the RTM method were used in bus bodies that operated with electricity, and they studied the mechanical properties and impact strengths of glass fibre–vinyl ester composites. Kim and Lee [17] studied the relation between surface qualities and shrinkage ratios after curing glass fibre-polyester resin composite parts produced by the RTM method. They experimentally measured the surface qualities and formations of the surface contour lines related to the fibre volume fraction, and then designed and produced the bus inner panels according to the obtained results. Studies on RTM glass fibre-polyester composites have mainly focused on the shrinkage and warpage problems of these materials after curing [18, 19].

Recently, Karahan et al. investigated low velocity impact [20], bending [21] and compression [22] properties of glass-vinyl ester composites. Zahid et al. [23] experimentally investigated the interlaminar shear strength of glass fibre-reinforced thermoplastic polyurethane (TPU) and epoxy-based thermoset composites enhanced with multi-walled carbon nanotubes (MWCNTs) and compared the performance of thermoplastic and thermoset composites. Karahan et al. [24] studied the impact and mechanical properties of hybrid composites made with natural and glass fibres. They found that the impact properties increased in hybrid structures. Karahan and Karahan [25] investigated the impact properties of hybrid composites woven from synthetic fibres, including glass, carbon, and aramid, and compared these with 100% glass fibre composites. Karahan et al. [26] investigated the effects of resin type on the mechanical properties and impact resistance of glass fibre composites.

The purpose of this study is to investigate the impact resistance of polyester resin composites used in the automotive industry, reinforced with randomly discontinuous and continuous glass fibre mats and glass fibres produced by hand lay-up, RTM, and SMC moulding methods. The mechanical properties of the composite plates were determined for this purpose. The impact strength was determined using the Charpy test. To determine the deformation of the materials after impact, the samples exposed to a low-speed weight drop were applied a 3-point flexural bending test, and their strength losses were determined.

EXPERIMENTAL

The reinforcement materials and their properties that were used in hand lay–up and RTM methods are given in table 1. CE 92 N8 type unsaturated polyester was used as a resin. Methyl Ethyl Ketone Peroxide (50% active) was used for curing with a ratio of 2%, and 6% Cobalt Naphthenate was used with a ratio of 0.25% as hardener and catalyst. In the SMC method, two ready compounds with different fibre volume fractions were used. The compound was in the form of a non-cured layer including fibre, resin and other filler and additives. The ratios of used SMC composite contents are given in table 2.

Hand lay-up, RTM and SMC moulding methods were used in the production of composite plates with dimensions of 300×300×4 mm. In table 3, the reinforcement elements and resin amounts in plates produced by hand lay-up and RTM methods can be found. In the hand lay-up operation, resin was

Table 1

THE REINFORCEMENT MATERIAL TYPES USED IN HAND LAY-UP AND RTM SAMPLES			
Material type	**Glass fibre type**	**Weight (g/m^2)**	**Supplier**
Randomly continuous glass fibre mat-U850	E-glass continuous filament	300	Vetrotex-Saint Gobain
Randomly discontinuous glass fibre mat-EMAT-1	E-glass discontinuous fibre	450	Cam Elyaf Inc.
Randomly discontinuous stitched glass fibre mat	E-glass discontinuous fibre	450	Cam Elyaf Inc.

Table 2

SMC COMPOSITE RATIOS AND PLATE THICKNESS OPTIMIZATION		
SMC materials	**SMC-1**	**SMC-2**
Discontinuous glass fibre (%)	22	28
Polyester resin (%)	26	28
Calcium Carbonate filler (%)	48	40
Pigment and thickener additives (%)	4	4
Total (%)	100	100
The thicknesses of finished plates (mm)	3.8	4

applied to glass fibre mats by a roll and left for curing. In the RTM method, resin injection was performed at a pressure of 3 bar, and the material was left under pressure at room temperature for 45 minutes to cure. In the SMC method, moulding was carried out under a pressure of 60 kg/cm^2 and a temperature of 140ºC. The samples were left to cure for 5 minutes. To determine the mechanical properties of the materials, their tensile strength and modulus were primarily measured. For this purpose, the breaking load and breaking strain were first determined. The tests were conducted using an HTE Hounsfield tension test device with 50 kN capacity, according to ASTM D638 standards. Tensile strength and elastic modulus were calculated using equations 1 and 2, respectively:

$$\sigma_C = \frac{F}{w \cdot t} \tag{1}$$

where σ_C is tensile strength (MPa), F – maximum load (N), w – sample width (mm), and t – sample thickness (mm).

$$E_C = \frac{\sigma_C}{\varepsilon} \;\; ; \;\; \varepsilon = \frac{\Delta l}{l_0} \tag{2}$$

Here, E_C is elastic modulus, ε – breaking strain, l_0 – initial sample length (mm), and Δl – breaking elongation (mm).

In order to determine the impact resistance, a low-speed weight drop method was used. Spherical-ended weights of 1 kg, with a 45 mm diameter, were dropped from 1 m onto the samples. The strength losses were determined using a 3-point flexural bending test. Samples were supported from 2 sides during the weight drop as shown in figure 1.

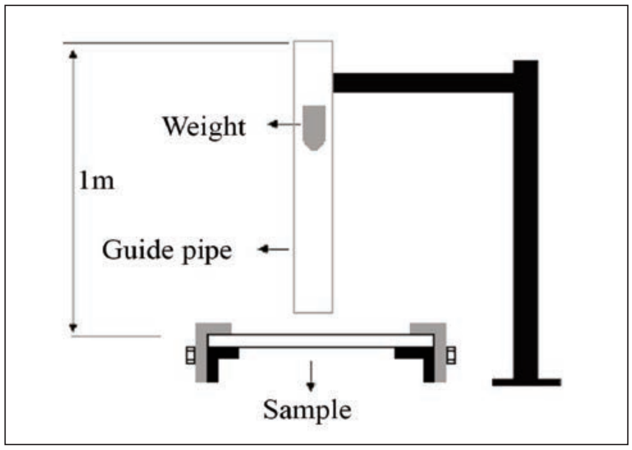


Fig. 1. Fixing of the samples from two sides during weight drop

The losses in mechanical properties of the samples after impact were determined by a 3-point bending test. The 3-point bending tests were performed using an Instron 4301 device according to ASTM D790 standard. The bending strength and bending modulus were calculated using equations 3 and 4, respectively. Here, σ_{CF} is the bending strength of the composite plate, E_{CF} – the bending modulus of the composite plate, F – maximum force (N), l – composite

Table 3

REINFORCEMENT ELEMENTS AND FIBRE VOLUME FRACTIONS IN HAND LAY-UP AND RTM COMPOSITE PLATES					
Production method	**Reinforcement materials**	**Total weight of reinforcement materials (g)**	**Weight of finished plate (g)**	**Fibre volume fraction (%)**	**Thickness of finished plate (mm)**
Hand lay-up	3 plies EMAT-1 discontinuous mat	121.5	587.85	20.66	4.4
RTM-1	3 plies U850 continuous mat	81	442.24	18.32	3.6
RTM-2	2 plies stitched mat + 1 ply U850 continuous mat	108	486.73	22.18	4

plate length (mm), w – plate width (mm), t – plate thickness (mm), m – tan α, is the slope of the load-elongation curve of the elastic region.

The impact strength of the samples was determined using a KSG-70 type Charpy test device in accordance with DIN 53453 standard. The samples were tested without notches. Following the Charpy tests, impact strength was calculated using equation 5. Here, K_C represents the impact strength (J/m^3), A_C – the fracture energy (J), l – the composite plate length (mm), w – the plate width (mm), and t – the plate thickness (mm).

$$\sigma_{CF} = \frac{3 \cdot F \cdot l}{2 \cdot w \cdot t^2} \quad (3)$$

$$E_{CF} = \frac{m \cdot l^3}{4 \cdot w \cdot t^3} \quad (4)$$

$$K_C = \frac{A_C \cdot 10^9}{w \cdot t \cdot l} \quad (5)$$

RESULTS AND DISCUSSION

To determine the mechanical properties of the composite plates produced using different methods, the tensile load and breaking strain were initially measured. Based on these results, the tensile strength and elastic modulus were calculated using equations 1 and 2. The results are presented in table 4. In the hand lay-up method, a discontinuous and randomly distributed mat was used, resulting in a composite plate with approximately 20% fibre volume fraction. The tensile strength of this plate was around 50 MPa, but a 20% deviation in strength and modulus values is noteworthy. The reason for this phenomenon is attributed to air voids in the plate, which weaken the structure. Figure 2 shows the air voids within the composite plate structure produced using the hand lay-up method.

In the structure produced by randomly distributed felt, fibres gather during the resin impregnation, leading to resin-rich regions and deteriorating the homogeneity of the structure. This can be considered as another factor for the deviation between the values. No air voids are left in the composite plate structure produced by the RTM moulding method, so the structure is denser. The fibre volume fraction is about 18% in the RTM-1 composite plates produced using continuous felt. The volume fraction of this plate is lower compared to the hand lay-up method, but the tensile strength is 12% higher, and the elastic modulus is 50% higher. This shows that the stiffness of the continuous felt reinforced composite plate produced by the RTM method is higher. Moreover, the low standard deviation demonstrates the homogeneity of the structure.

Continuous mat reinforced RTM composites are a good solution for obtaining high strength and high stiffness at the same time. However, due to the high cost of continuous mats, they are used together as a hybrid with discontinuous felts in the RTM process while producing the parts for the automotive industry. Practical applications have shown that if discontinuous, randomly distributed felts are used in the RTM process, fibres disintegrate during resin injection, which prevents a homogeneous structure from being obtained. For this reason, stitched discontinuous randomly distributed felts have been developed. These structures are generally suitable for resin injection but cannot be used alone. They are generally used together with continuous felts. In the RTM-2 composite plate, two layers of stitched, randomly distributed felts were used together with one layer of continuous, randomly distributed felt. The fibre volume fraction in this felt is about 22%. Although this ratio is 4% higher than that of the RTM-1 composite plate, the increase in tensile strength is not significant. However, the elastic modulus is 37% higher. But there has been a 17% standard deviation in the modulus values of the RTM-2 composites.

Although the fibre volume fraction of the SMC-1 composite plate is 22%, its tensile strength has been

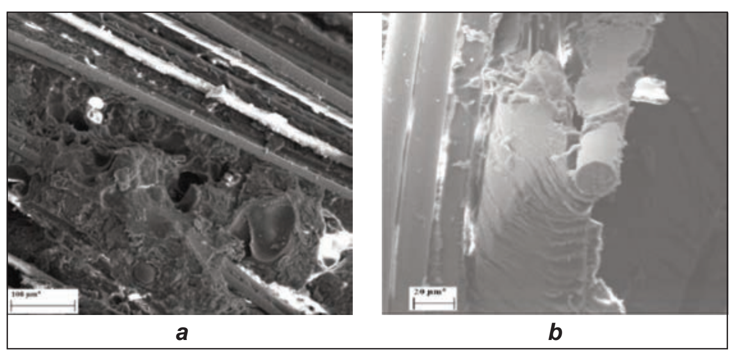


Fig. 2. The air voids between the fibres of the composite plate are produced by the hand lay-up method and resin-rich regions: *a* – x400; *b* – x1000

Table 4

MECHANICAL PROPERTIES OF COMPOSITE PLATES FROM HAND LAY-UP, RTM, AND SMC METHODS				
Production method	**Maximum load, F (kN)**	**Breaking strain, ε**	**Tensile strength, σ_C (MPa)**	**Elastic Modulus, E_C (MPa)**
Hand lay-up	4.43 ± 0.96	0.090 ± 0.01	50.30 ± 10.92	587.20 ± 101.92
RTM-1	4.06 ± 0.13	0.060 ± 0.01	56.44 ± 1.80	891.47 ± 71.54
RTM-2	4.65 ± 0.40	0.048 ± 0.005	58.15 ± 4.99	1227.64 ± 214.47
SMC-1	2.65 ± 0.081	0.044 ± 0.003	34.89 ± 1.062	790.46 ± 58.29
SMC-2	5.77 ± 0.22	0.070 ± 0.01	72.18 ± 2.75	984.89 ± 127.76

determined to be around 35 MPa. Since it is produced under high pressure, no air voids are present in the structure. However, in the SMC composition, a significant amount of calcium carbonate is used as a filler alongside fibre and resin. Calcium carbonate behaves like air voids in the structure and decreases the strength significantly (figure 3). As shown in figure 3, calcium carbonate particles negatively affect fibre-matrix interface adhesion within the structure. Figure 4 compares the SMC composite with the hand lay-up and RTM composites. However, considering the elastic modulus value, it seems that calcium carbonate increases the stiffness. The fibre volume fraction in the SMC-2 plate is 28%. The 6% increase in the ratio raised the tensile strength more than twofold. However, the increase in elastic modulus compared with the SMC-1 plate is 24%. The decrease in the filler ratio and the increase in the resin ratio cause the ductility of the structure to increase slightly. Although there is a significant increase in strength due to the glass fibre volume fraction, the same increase did not occur in the stiffness of the material.

The most important performance parameters in automotive composites are impact strength and the amount of energy required for fracture. The impact strengths of the materials produced for this purpose were determined using the Charpy test. The impact

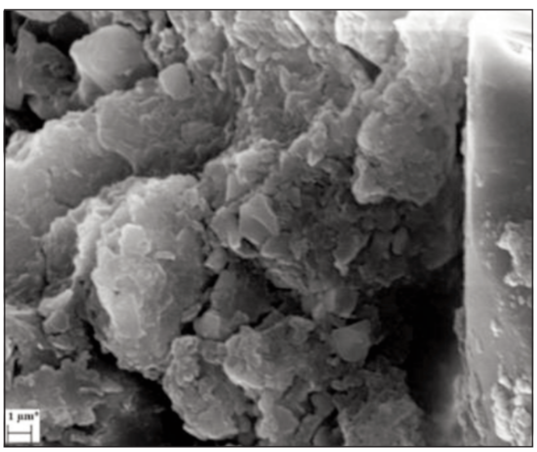
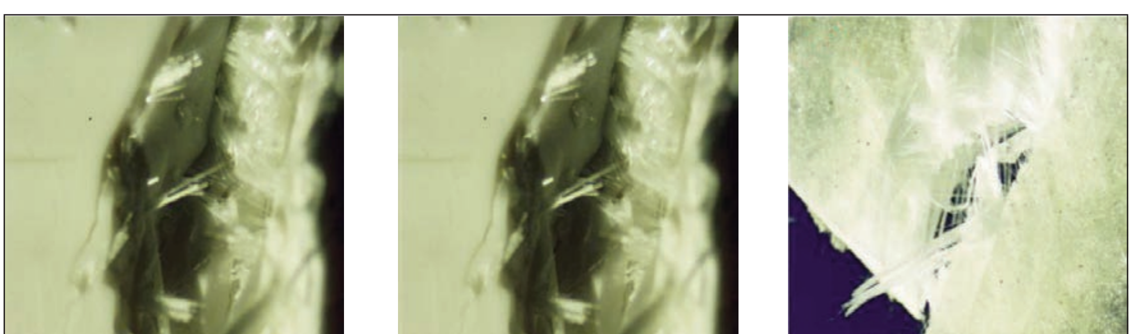


Fig. 3. Calcium carbonate particles in SMC structure and fibre-matrix interface (×10,000)

Table 5

IMPACT STRENGTHS OF COMPOSITE PLATES FROM HAND LAY-UP, RTM, AND SMC METHODS		
Production method	**Fracture energy, A_C (J)**	**Impact strength, K_C (kJ/m^3)**
Hand lay-up	1.16 ± 0.38	478.16 ± 155.73
RTM-1	1.18 ± 0.21	596.68 ± 102.92
RTM-2	1.61 ± 0.32	731.06 ± 145.46
SMC-1	0.64 ± 0.11	304.17 ± 51.45
SMC-2	1.39 ± 0.18	629.87 ± 84.74

strengths were calculated using equation 5. The results are in table 5. When the results were analysed, it was seen that the minimum impact strength was observed in the SMC-1 composite material. According to this result, a high filler content decreases the toughness of the structure. In SMC composites, the impact strength and toughness of the structure increase in relation to the fibre volume fraction. Although a large amount of air voids are present in composite plates produced by the hand lay-up method, they exhibit greater impact strength compared with the SMC-1 composite materials. However, there is approximately a 30% deviation in the impact strength values of the composites produced with the hand lay-up method. The reason for this phenomenon is the resin–rich regions formed due to air voids and disordered distribution of fibres in the structure. The impact strength in the RTM-1 continuous felt-reinforced composite material is greater than that produced with the hand lay-up method, despite its lower fibre volume fraction. In RTM-2 composite material, a 4% increase in fibre volume fraction results in a 23% increase in fracture strength. The hybrid structure used in the RTM-2 composite material offers several advantages: The stitched mat increases the fibre volume fraction and toughness, while the discontinuous mat prevents rupture after fracture and increases the ductility of the material at the same time. Figure 5 illustrates the fracture of the RTM composite material, revealing a brittle fracture. As a result, the energy required for breaking increases. In figure 6, while the fibres of discontinuous felt break completely after impact, the thinner filaments in



a *b* *c*

Fig. 4. The comparison of surface and inner structures of:
a – SMC; *b* – RTM; *c* – hand lay-up composites

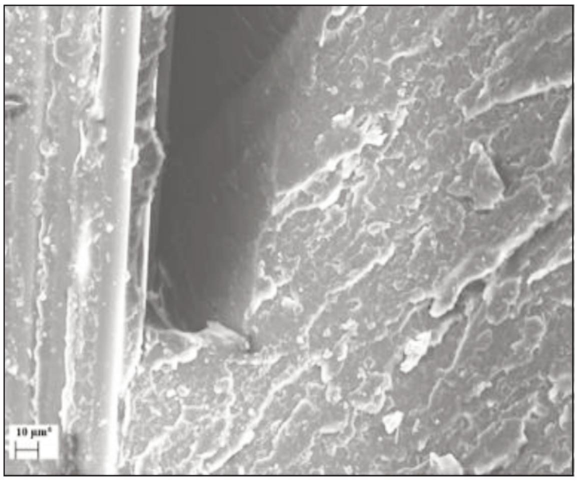


Fig. 5. Brittle fracture behaviour in RTM composite structure (×1000)

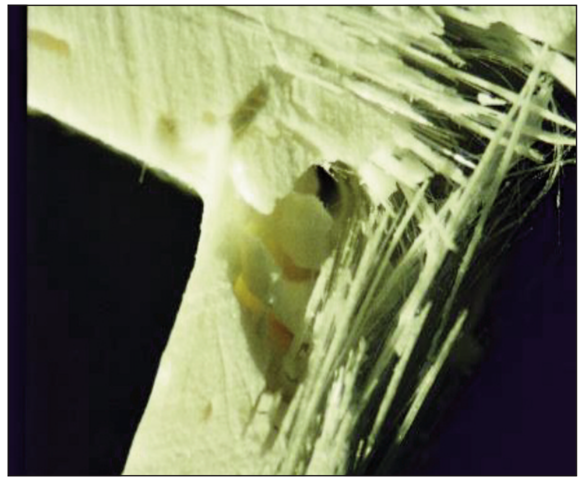


Fig. 6. The fracture in the RTM-2 composite part after impact

the continuous remain intact, maintaining the structure's integrity.

Fracture toughness is an extremely important parameter, especially for automotive parts where collision is important. However, while information such as Poisson's ratio and elastic modulus is needed to find this value, it is certainly a parameter directly related to the impact energy. Therefore, a comparison based on the impact energy value instead of finding the value gives almost the same trend [27].

The impact strength and elastic modulus of the composite plates produced by hand lay-up, RTM and SCM methods are compared in figure 7. As seen in the figure, the impact strength increases similarly to the elastic modulus. However, this trend is not valid for SMC-1 plates. The toughness of the structure is very low due to the excessive amount of filler in SMC-1 composite parts. However, with a 6% increase in the fibre volume fraction, the toughness and energy absorption capability of the structure increase by approximately twofold. In this case, it can be concluded that the increase in the fibre volume fraction has the greatest effect on impact strength [28–31].

In automotive composites, one of the biggest problems, especially in exterior body and bonnet parts, is

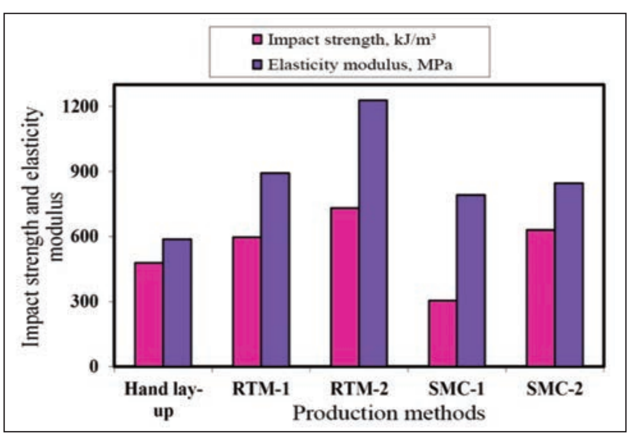


Fig. 7. The impact strengths and elasticity modules of Hand lay-up, RTM and SMC composites

the small bumps during parking. This causes small cracks in the composite parts, decreasing the strength of the structure. In this study, this problem was simulated by a low-speed weight drop method. The bending strength and modulus values of the weight-dropped samples were determined using a 3-point flexural bending test, and losses in strength and modulus values were compared to parts that did not undergo weight drop. Bending strength and modulus were calculated using equations 3 and 4, respectively. Results are given in table 6. According to these results, bending strength and modulus increase with increasing fibre volume fraction, but losses in bending strength occur after impact. Composite parts produced using the hand lay-up method have low bending strength, but due to their ductile structure, the loss in bending strength after the impact is low. Moreover, the bending strength of RTM composites increased threefold with a 4% increase in fibre volume fraction. However, as the fibre volume fraction increases, the post-impact loss in bending strength also increases. It was observed that bending strength was halved in RTM-2 composite parts. Interestingly, the decrease in bending modulus is limited. The simultaneous decrease in displacement value and strength limits the change in modulus. This phenomenon can be observed in the load-displacement curve in figure 8. Cracks that occur in the structure after a weight drop decrease the structure's elasticity, and rupture occurs where the cracks accumulate. In this case, both bending and displacement decrease.

In SMC composites, a 6% increase in the fibre volume fraction results in a threefold increase in bending strength. The loss in bending strength also increases after impact due to the higher fibre volume fraction, but this loss is less significant than in RTM composites. The decrease in bending modulus is approximately 5%, similar to the other composites. As a result, it can be concluded that while the fibre volume fraction increases, the bending strength improves, but the post-impact bending strength losses also increase. Moreover, significant changes do not occur in the bending module after impact.

Table 6

3-POINT BENDING TEST RESULTS FOR COMPOSITE PLATES FROM HAND LAY-UP, RTM, AND SMC METHODS						
Production method	**Bending strength, σ_{CF} (MPa)**		**% difference**	**Bending modulus, E_{CF} (MPa)**		**% difference**
	Non-impacted	**Impacted**		**Non-impacted**	**Impacted**	
Hand lay-up	28.92±7.2	27.01±7.5	6.6	658±132	621±137	5.6
RTM-1	25.83±2.8	21.08±4.2	18.3	1143±86	1086±94	4.9
RTM-2	76.53±4.8	34.56±5.1	54.8	2276±287	2162±264	5
SMC-1	15.27±2.5	15.11±2.2	1.04	976.9±72	922±86	5.5
SMC-2	50.88±6.1	42.34±5.7	16.8	1687±182	1618±195	4.1

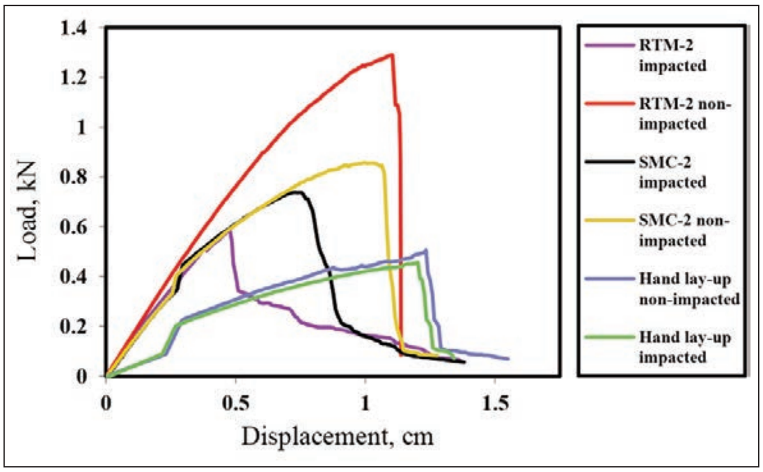


Fig. 8. Load-displacement results of the 3-point bend test results applied to impacted and non-impacted samples

CONCLUSION

The following conclusions were drawn from this study:

- With increasing fibre volume fraction, mechanical properties and impact strength improve. However, calcium carbonate used as a filler reduces the mechanical properties and impact strength of the composite structure, making it more brittle. It is very difficult to maintain homogeneity in composite parts produced by the hand lay-up method. The mechanical performance of such parts is limited, and they should not be used in critical applications where strength is required. The mechanical properties of composite parts produced using the RTM method increase with fibre volume fraction. Such parts can be used in applications requiring high performance. Their energy-absorbing capability and impact strength are higher compared with composites produced using the hand lay-up and SCM methods. However, RTM composites lose most of their strength after impact.
- The mechanical properties of SCM composites improve with fibre volume fraction. However, due to the high filler content in its structure, compared to RTM composites, the mechanical properties and energy absorbing capability decrease more when the fibre volume fraction is low. As fibre volume fraction increases, these disadvantages diminish. Moreover, the strength losses of SMC composites after impact are smaller than those of RTM composites. Although strength losses occurred after impact, the losses in modulus were very limited.

REFERENCES

[1] Vieyra, H., Molina-Romero, J.M., Calderón-Nájera, J.d.D., Santana-Díaz, A., *Engineering, Recyclable, and Biodegradable Plastics in the Automotive Industry: A Review*. In: Polymers, 2022, 14, 16, 3412, https://doi.org/10.3390/polym14163412

[2] Ahmad, H., Markina, A.A., Porotnikov, M.V., Ahmad, F., *A review of carbon fibre materials in the automotive industry*. In: IOP Conference Series: Materials Science and Engineering, 2020, 971, 3, 032011, https://doi.org/10.1088/1757-899X/971/3/032011

[3] Fan, J., Njuguna, J., *An introduction to lightweight composite materials and their use in transport structures*, In: Lightweight Composite Structures in Transport, J. Njuguna, Ed., ed: Woodhead Publishing, 2016, 3–34

[4] Wazeer, A., Das, A., Abeykoon, C., Sinha, A., Karmakar, A., *Composites for electric vehicles and automotive sector: A review*. In: Green Energy and Intelligent Transportation, 2023, 2, 1, 100043, https://doi.org/10.1016/j.geits.2022.100043

[5] Henning, F., Kärger, L., Dörr, D., Schirmaier, F.J., Seuffert, J., Bernath, A., *Fast processing and continuous simulation of automotive structural composite components*. In: Composites Science and Technology, 2019, 171, 261–279, https://doi.org/10.1016/j.compscitech.2018.12.007

[6] Khan, L.A., Mahmood, A.H., Hassan, B., Sharif, T., Khushnod, S., Khan, Z.M., *Cost-effective manufacturing process for the development of automotive from energy efficient composite materials and sandwich structures*, In: Polymer Composites, 2014, 35, 1, 97–104, https://doi.org/10.1002/pc.22638

[7] El-Wazery, M., El-Elamy, M., Zoalfakar, S., *Mechanical properties of glass fibre reinforced polyester composites*. In: International Journal of Applied Science and Engineering, 2017, 14, 3, 121–131, https://doi.org/10.6703/IJASE.2017.14(3).121

[8] Asadi, A., Miller, M., Singh, A.V., Moon, R.J., Kalaitzidou, K., *Lightweight sheet moulding compound (SMC) composites containing cellulose nanocrystals*. In: Composite Structures, 2017, 160, 211–219, https://doi.org/10.1016/j.compstruct.2016.10.051

[9] Heudorfer, K., Bauer, J., Caydamli, Y., Gompf, B., Take, J., Buchmeiser, M.R., Middendorf, P., *Method of Manufacturing Structural, Optically Transparent Glass Fibre-Reinforced Polymers (tGFRP) Using Infusion Techniques with Epoxy Resin Systems and E-Glass Fabrics*. In: Polymers, 2023, 15, 9, 2183, https://doi.org/10.3390/polym15092183

[10] Guha, P., *Innovations in Automotive Composites through the Years: Strength and Gaps*, In: Composites Innovation, ed: CRC Press, 2021, 69–81

[11] Lee, H.-K., Simunovic, S., *Damage Behavior of Aligned and Random Fibre Reinforced Composites for Automotive Applications*, In: SAMPE-ACCE-DOE Advanced Composites Conference, 1999, 196–205

[12] Santulli, C., Brooks, R., Long, A.C., Warrior, N.A., Rudd, C.D., *Impact properties of compression moulded commingled E-glass–polypropylene composites*. In: Plastics, Rubber and Composites, 2002, 31, 6, 270–277, https://doi.org/10.1179/146580102225004983

[13] Piry, M., Michaeli, W., *Stiffness and failure analysis of SMC components considering the anisotropic material properties*. In: Macromolecular Materials and Engineering, 2000, 284-285, 1, 40–45

[14] Oldenbo, M., Fernberg, S. P., Berglund, L.A., *Mechanical behaviour of SMC composites with toughening and low density additives*. In: Composites Part A: Applied Science and Manufacturing, 2003, 34, 9, 875–885, https://doi.org/10.1016/S1359-835X(03)00155-6

[15] Gregl, B.V., Larson, L.D., Sommer, M., Lemkie, J.R., *Formulation advancements in hollow-glass microspheres filled SMC*, In: SAE transactions, 1999, 797–805

[16] Sheu, M.-F., Lin, Y.-K., Chuang, Y.-H., Chang, Y.-C., Ong, C.-L., *Process development for composite electric bus body using resin transfer moulding technology*. In: Society for the Advancement of Material and Process Engineering, Bridging the Centuries with SAMPE's Materials and Processes Technology, 2000, 45, 2332–2343

[17] Kim, P.J., Lee, D.G., *Surface quality and shrinkage of the composite bus housing panel manufactured by RTM*, In: Composite Structures, 2002, 57, 1, 211–220, https://doi.org/10.1016/S0263-8223(02)00068-5

[18] Huang, M.-C., Tai, C.-C., *The effective factors in the warpage problem of an injection-molded part with a thin shell feature*, In: Journal of Materials Processing Technology, 2001, 110, 1, 1–9, https://doi.org/10.1016/S0924-0136(00)00649-X

[19] Patel, N., Patel, K., Chaudhary, V., Gohil, P., *Investigations on drilling of hybrid basalt/glass polyester composites*, In: Australian Journal of Mechanical Engineering, 2022, 20, 4, 1154–1163, https://doi.org/10.1080/14484846.2020.1784560

[20] Karahan, M., Gül, H., Ivens, J., Karahan, N., *Low velocity impact characteristics of 3D integrated core sandwich composites*. In: Textile Research Journal, 2012, 82, 9, 945–962, https://doi.org/10.1177/0040517512436832

[21] Karahan, M., Gul, H., Karahan, N., Ivens, J., *Static behavior of three-dimensional ıntegrated core sandwich composites subjected to three-point bending*, In: Journal of Reinforced Plastics and Composites, 2013, 32, 9, 664–678, https://doi.org/10.1177/0731684412474857

[22] Karahan, M., Karahan, N., Gul, H., Ivens, J., *Quasi-static behavior of three-dimensional integrated core sandwich composites under compression loading*, In: Journal of Reinforced Plastics and Composites, 2013, 32, 5, 289–299, https://doi.org/10.1177/0731684412471091

[23] Zahid, S., Nasir, M.A., Nauman, S., Karahan, M., Nawab, Y., Ali, H.M., Khalid, Y., Nabeel, M., Ullah, M., *Experimental analysis of ILSS of glass fibre reinforced thermoplastic and thermoset textile composites enhanced with multiwalled carbon nanotubes*. In: Journal of Mechanical Science and Technology, 2019, 33, 1, 197–204, https://doi.org/10.1007/s12206-018-1219-0

[24] Karahan, M., Ozkan, F., Yildirim, K., Karahan, N., *Investigation of the properties of natural fibre woven fabrics as a reinforcement materials for green composites*, In: Fibres & Textiles in Eastern Europe, 2016, 4, 118, 98–104

[25] Karahan, M., Karahan, N., Effect of weaving structure and hybridization on the low-velocity impact behavior of woven carbon-epoxy composites, In: Fibres & Textiles in Eastern Europe, 2014, 22, 3, 109–115

[26] Karahan, M., Özyurt, İ., Atalay, Ş.Ö., Turan, Ş.Y., Haji, A., Karahan, N., *Comparative study of virgin and recycled polyethylene terephthalate and polypropylene intermingled thermoplastic composites*, In: Polymer Composites, 2024, https://doi.org/10.1002/pc.29209

[27] Liu, H., Yan, J., Li, A., He, Z., Xie, Y., Yan, H., Huang, D., *A Relationship between Fracture Toughness Kc and Energy Release Rate Gc According to Fracture Morphology Analysis*, In: Crystals, 2024, 14, 8, 740, https://doi.org/10.3390/cryst14080740

[28] Karahan, M., Yiğit, F.G., *Investigation of Aging Effects of Polymeric Composite Materials due to Ozone and Humidity*, In: Polymers for Advanced Technologies, 2025, 36, 7, e70245

[29] Karahan, M., Yildirim, K., *Low velocity impact behaviour of aramid and UHMWPE composites*, In: Fibres & Textiles in Eastern Europe, 2015, 23, 3, 97–105

[30] Karahan, M., Abbas, A., Hussain, M., *Commingled synthetic and natural fibers preforms reinforced composites: a simultaneous comparison of mechanical properties*, In: Polymer Composites, 2025, https://doi.org/10.1002/pc.29653

[31] Ari, A., Karahan, M., Karahan, N., Yedekçı, B., *Comparison of mechanical and flammability properties of thermoplastic and thermoset matrix glass fibre woven fabric composites*, In: Industria Textila, 2024, 75, 5, 565–576, http://doi.org/10.35530/IT.075.05.2023103

Authors:

MEHMET KARAHAN[1], AMINODDIN HAJI[2]

[1]Vocational School of Technical Sciences, Bursa Uludag University, 16059, Bursa, Türkiye
e-mail: ahaji@yazd.ac.ir

[2]Department of Textile Engineering, Yazd University, Yazd, Iran

Corresponding author:

MEHMET KARAHAN
e-mail: mkarahan@uludag.edu.tr