DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

INVESTIGATION OF IMPACT BEHAVIOR OF POLYMER COMPOSITE MATERIALS REINFORCED BY WOVEN FABRICS PRODUCED FROM NATURAL TEXTILE FIBRES

by
Melih KORKMAZ

September, 2021
IZMIR

INVESTIGATION OF IMPACT BEHAVIOR OF POLYMER COMPOSITE MATERIALS REINFORCED BY WOVEN FABRICS PRODUCED FROM NATURAL TEXTILE FIBRES

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We have read the thesis entitled **"INVESTIGATION OF IMPACT BEHAVIOR OF POLYMER COMPOSITE MATERIALS REINFORCED BY WOVEN FABRICS PRODUCED FROM NATURAL TEXTILE FIBRES"** completed by **MELİH KORKMAZ** under supervision of **PROF. DR. RAMAZAN KARAKUZU** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

The composite materials consist of least two materials. When the composites are compared with the metals and their alloys, they have many outstanding properties such as non-corrosion, high strength/weight ratio and ease of design. The fiber-reinforced composites are prevalently used in the industry. Generally, the synthetic fibers like carbon or glass usually were preferred. However, the synthetic fibers are hardly recycled in nature. Therefore, the natural fiber reinforced composites are begun to use as alternative in recent years. In this thesis, firstly, the flax fabrics were produced from the flax yarns by automated weaving machine in the different weft densities. After that, the flax woven reinforced composites were manufactured by vacuum assisted resin infusion molding (VARIM) method. Tensile, compression and shear tests were conducted to obtain modulus of elasticity, tensile and compressive strengths in warp and weft directions, Poisson’s ratio, shear modulus and shear strength by Shimadzu tensile testing machine and test apparatus. Impact tests were carried out for different impact energies to obtain impact resistance and absorbed energy by CEAST Fractovis Plus impact test machine. Obtained results were compared according to the different yarn densities and it is seen that yarn density has a significant effect on mechanical properties, strengths and impact performance of the woven flax reinforced composites.

Keywords: Flax fiber, woven fabric, polymer composite, mechanical properties, yarn density, low velocity impact

DOĞAL TEKSTİL LİFLERİNDEN ÜRETİLMİŞ DOKUMA KUMAŞ TAKVİYELİ POLİMER KOMPOZİT MALZEMELERİN DARBE DAVRANIŞLARININ İNCELENMESİ

ÖZ

Kompozit malzemeler en az iki bileşen içerirler. Kompozit malzemeler metaller ve alaşımlarıyla karşılaştırıldığında korozyona uğramama, yüksek hacim/ağırlık oranı ve tasarım kolaylığı gibi birçok üstün özelliklere sahiptirler. Fiber takviyeli kompozit malzemeler endüstride yaygın olarak kullanılmaktadır. Genellikle karbon ya da cam gibi sentetik fiber takviye elemanı tercih edilmektedir. Ancak sentetik fiberlerin doğada geri dönüşümü oldukça zordur. Bundan dolayı, son zamanlarda doğal fiber takviyeli kompozit malzemeler, sentetik takviye elemanlı kompozit malzemelere bir alternatif olmaya başlamıştır. Bu tezde, ilk olarak keten iplikler kullanılarak, atkı yönünde farklı sıklıklara sahip keten kumaşlar dokuma tezgahında üretilmiştir. Daha sonra, dokuma keten takviyeli kompozitler vakum destekli reçine infüzyon kalıplama metodu (VARIM) kullanılarak üretilmiştir. Kayma modülü ve kayma mukavemeti, Poisson oranı, atkı ve çözgü yönündeki elastisite modülü, çeki ve bası mukavemetlerini belirlemek için Shimadzu çekme test makinası ve aparatlar kullanılarak çekme, basma ve kayma testleri yapılmıştır. Kompozitin darbe direncini ve absorbe ettiği enerjiyi elde etmek için CEAST Fractovis Plus darbe cihazı kullanılarak darbe testleri gerçekleştirilmiştir. Elde edilen sonuçlar farklı iplik sıklıklarına bağlı olarak birbirleriyle karşılaştırılmış ve iplik sıklığının dokuma keten takviyeli kompozitlerin mekanik özellikleri, mukavemetleri ve darbe performansı üzerine önemli etkiye sahip olduğu görülmüştür.

Anahtar kelimeler: Keten lif**,** dokuma kumaş, polimer kompozit, mekanik özellikler, iplik sıklığı, düşük hızlı darbe

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CHAPTER ONE
INTRODUCTION AND GENERAL INFORMATION

1.1 Introduction

In this thesis, 1X3 twill fabrics were produced from flax yarns. The fabrics were differentiated according to their weft densities, which were 6, 8 and 10 yarns/ cm. The diversified flax woven fabrics were converted the composites thanks to the vacuum assistant resin infusion molding (VARIM). The orientations of reinforcements were settled in $[0]_3$ and $[0]_{12}$ for mechanical and low velocity impact tests, respectively. The tensile, compressive and shear tests were applied to the composite for mechanical characterization. Then, the low velocity impact properties were investigated for flax woven reinforced composites in terms of the weft densities.

1.2 General Information and Previous Studies

1.2.1 Composite Materials

Composites have been used during the human history. The first composite was plywood, which were glued wood strips at different angels, at 3400 BC in the Mesopotamia (‘Compositeslab’,b.t.). In addition, villagers have built their house thanks to the mudbrick since antiquity.

Composite is taken place at least two different materials, which are matrix and reinforcement, the existence material has better properties than its components. While the polymers, metals or ceramics can be used as matrix in the composites, the fibers or metals can be chosen for reinforcements.

The fiber reinforced polymers constitutes the enormous volume of composite market because they present advantages to the producers such as high strength-stiffness/ weight ratio, design flexibility and non- corrosion structure. For this reason, they are demanded from different industries like defense, aviation, automotive, medical and so on.

1.2.1.1 Classification of Composite Materials

Composites can be classified according to the type of matrix or reinforcement materials.

1.2.1.1.1 Classification According to the Matrix. The matrix transfers the load to the reinforcements and give the general shape to the composite. In addition, the reinforcements are protected from environmental damages thanks to the matrix. Composite materials are divided three groups in terms of the matrix types. These are polymer, metal and ceramic composites.

Polymer matrix composites (PMC) are most preferred materials among the all three types. Thermoset or thermoplastic polymers can be used as polymer materials in these composites.

Thermoset matrix has more resist to plastic deformations because they have stiff structure and well penetrate with reinforcement. The epoxy, vinyl ester or polyester can be used as thermoset matrix in the composites. When the thermoset resin is mixed with hardener, the viscosity of matrix is raised. So that, it is significant to working with the thermoset matrix is that the reinforcement should be processed according to the curing temperature and time of matrix.

Thermoplastic matrix is another polymer to be used in the composites. If the thermoplastic matrix is exposed the higher temperature than its glass transition temperature, the matrix is melt. Due to its characteristic structure, the thermoplastic matrix is less brittle than thermosets. Moreover, the toughness of thermoplastics is higher and it can be easily repaired even after than produced. The nylon, polypropylene or polyethylene can be given as examples for main types of thermoplastic matrix.

Metal matrix is one of the three types of matrix types. This matrix, as easily predicted with name, include metals like a magnesium, aluminum or titanium. When metal matrix composites (MMC) compare with PMC, it has higher elasticity, conductivity, temperature resistance, etc.

Ceramic matrix generally preferred at application areas in which the temperature is high. While the polymers and metals can resist the temperature up to 400°C and 1000°C, the ceramics can service up to 1500°C (Kaw, 2006).

1.2.1.1.2 Classification According to the Reinforcement. The strength and stiffness of the composites are characterized by the reinforcements. The reinforcements can be categorized to the four groups as fibrous, laminates, particulate and their combinations (Jones, 1999).

The fibers are long and continue along the matrix in the fibrous composites. They can be used at different angles and sizes according to the purposed mechanical properties of material. The glass, carbon and para-aramid are most preferred raw materials for fibrous composites.

The laminated composite materials consist of at least two bonded fibrous laminates. The laminates can be placed at different angles with respect to the fiber architecture of composite. Thanks to their high strength and stiffness values, the laminated composites are mostly used for structural applications.

The particulate composite materials include particles, which are randomly scattered in the matrix. The latest reinforcement type is the combinations of some or all of the three reinforcement types (Jones, 1999). The fiber reinforced nanocomposite can be shown as an example for this group because it contains either particle or fiber.

1.2.1.2 Manufacturing Methods of Composite Materials

Composite materials are currently used lots of application fields. According to the demanded properties, the composites can be obtained by different production methods. Besides, manufacturing methods can be chosen in terms of the components of composite materials. The main manufacturing methods are open and closed moldings.

1.2.1.2.1 Open Molding Method. Composite materials need curing process to have higher strength and stiffness values. In this method, resins and reinforcements are contact with air, while they are curing. Open molding method involve hand lay-up, spray-up and filament winding.

In the hand lay-up method, the reinforcement is placed with hand according to the mold. Then, resin is added. For instance, the boats and tubes are produced with this method. The spray lay-up method has same procedures with hand lay-up method except the chopper gun. While the short fibers and resins are mixed in catalyst, fibers are cut by means of the chopper gun.

Filament winding is chosen for various purposes such as pipes, case of rocket motors and so on. After continue fiber are passed through the resin, it is rotated along to the cylindrical mold. Although the fibers do not include the intersections, the complex shapes can be easily obtained with the mentioned method.

1.2.1.2.2 Closed Molding Method. The closed molding method is more preferred than the open molding method because it gains better strength properties to the material. When the composites are produced with closed molding method, the reinforcements and fibers are completely covered. The vacuum bag molding, vacuum assistant resin infusion molding, resin transfer molding, compression molding, pultrusion, reinforced reaction injection molding, centrifugal casting and continuous lamination are types of closed molding methods *('Compositeslab',b.t.)*.

In the vacuum bag molding method, the same procedure is followed with had lay-up method to mix fibers and resin. Then, the vacuum is applied to absorb the air from the material.

The vacuum is used for either absorb air or transfer resin around the reinforcements in the vacuum assistant resin infusion molding (VARIM). Due to the thermoset resins have lower viscosity, generally they are preferred to use in this method.

Compression molding is another most uses closed molding methods. Composites are squeezed and formed under the pressure, which is applied on the molds.

1.2.2 Natural Fiber Reinforced Composite (NFRC) Materials

The fiber reinforced composites are most demanded composite type thanks to their extraordinary properties. Furthermore, their usage areas are increasing day by day. Because of their advantages, the fiber reinforced composites are preferred at different application areas such as airplanes, boats or wind turbines. On the contrary, as the most of composite fibers are synthetic, the produced composites are not eco-friendly nature and cannot be decomposed with the time.

Natural fiber reinforced composites have been used as alternatives instead of synthetic fiber reinforced composites in the last decades. Natural fiber reinforced composites are divided into three classes which are cellulose from plants (cotton, sisal, flax, hemp, etc.), protein from animals (wool, angora, silk) and mineral (asbestos, basalt) (Guido et al., 2012). Natural fiber reinforced composites have many advantages in comparison with the man-made fiber reinforced composites as cost, recyclability and strength to use for different purposes. In addition, natural fiber reinforced composites have more specific properties than synthetic fiber reinforced composites. For instance, the flax reinforced composites have perfect energy absorbing capacity. Because of this, they and their carbon hybrid composites are demanded from the automotive industry to use.

1.2.3 Mechanical and Low Velocity Impact Behaviors of NFRC

NFRC have been increasingly used, after it was noticed that the man-made reinforced composites are dangerous for nature. Moreover, NFRC are cheap, light and have specific properties in comparison with the synthetic fiber reinforced composites.

The mechanical behaviors of composite materials have to be compatible for their usage area. As the synthetic fiber reinforced composites can be replaced with NFRC, the NFRC should have comparable mechanical properties. NFRC can't show homogeneous mechanical properties at their every point and synthetic fiber composites have more strength and stiffness values. However, NFRC can perfectly absorbed energy, eco-friendly and much cheaper. The energy absorbing capacity of composites is vital property to prefer them for structural application. The composites can be subjected to the low velocity impact loads while they are under the maintenance processes or in the application areas. It is complicated to detect the micro cracks and fractures in the composites. Because of this, many of the studies are focused to characterize the mechanical and impact behaviors of composites.

1.2.3.1 Previous Studies about Mechanical and Low Velocity Impact Behaviors of NFRC

A great deal of studies was carried out to investigate the mechanical and impact behaviors of NFRC. They examined NFRC according to the fiber architecture, type of the components or environmental properties. Stacking sequence of laminates is one of the significant fiber architecture and profoundly impress the strength, stiffness or resin absorption properties of composites.

Muralidhar (2013) produced NFRC with hand lay-up method. While the flax fabrics were used as reinforcements, the layers placed with different angles and plies. The configurations of samples are 8 plies [0°/0°], 8 plies [90°/0°], 16 plies [0°/0°/0°/0°], 16 plies [0°/90°/90°/0°], 16 plies [0°/+45°/-45°/0°] and their names were W1, W2, W3, W4, W5, respectively. The tensile and compression tests were applied to them at both directions. While the composites have similar strength and stiffness values at both sides, W1 has higher tensile strength and modulus at weft direction. Due to W2 has same fiber density at both side, it is shown similar strength and modulus at either weft or warp sides. In addition, 16 plies showed better strength and stiffness values in compressive test when compare with eight plies composites.

Nicolinco et al. (2021) choosed flax fabrics as reinforcements to produce their composites. They manufactured 16-layers composites and settled their orientation at 0˚, 90˚, ±45˚ and ±67.5˚ angles. They applied compression tests and aim to determine in plane plasticity and moduli of composites, which include different angle laminates. Besides, the Mesoscale Damage Theory (MDT) was applied to predict the damage and then the results were compared with test data. It was determined that the high plasticity and non-liner damages could be predicted for three orthotropic directions with the MDT.

Muralidhar (2013) produced flax reinforced composites, which have knitted rib reinforcements and the hand lay-up method was preferred to produce composites. When the fabrics converted to the composites, laminates were placed at different angles and number of plies. The tensile and compression tests were applied to the samples The configuration of composites are two plies [0°/0°], two plies [90°/0°], four plies [0°/0°/0°/0°], 4 plies [0°/90°/90°/0°], 4 plies [0°/+45°/-45°/0°]. The samples were named as K1, K2, K3, K4, K5, respectively. It was concluded that two plies composites shown better tensile strength than four plies composites. The composites have better tensile strength and high modulus at wale direction in comparison with the course direction. While K4 shown minimum tensile modulus, K3 have maximum modulus value. In addition, two plies composites displayed higher strain at failure than four plies composites.

Panzera et al. (2020) studied on the prepreg flax reinforced composites. They produced composites materials include laminates, which have different angles and number of plies. The orientation of composites were unidirectional 12 layers $[0]_{12}$ and 13 layers cross ply $[(0/90)3/\bar{0}]_{s}$. The tensile, the bending, the impact tests were applied the composites to investigate their static mechanical, fatigue and shear behaviors. The testing results were compared with either among them or unidirectional glass reinforced composites. According to the testing results, unidirectional (UD) flax reinforced composite was determined as optimum material for aerospace engineering fields. It shown higher specific tensile modulus and similar specific flexural modulus with UD glass reinforced composites.

The low velocity impact test is a significant method to understand the energy absorption, impact strength, impact resistance and damage examination of materials.

Ramakrishnan et al. (2021) produced composites, which were reinforced with 2X2 twill flax fabrics. The samples were diversified with respect to the types of matrix, which were the thermoset (epoxy) and the thermoplastic (polypropylene). The impact tests were applied to the composites with the drop tower impact machine. The impact tests were carried out at 3J, 6J, 9J, 12J and 15J energy levels. According to the obtained results, both samples shown similar impact resistances. However, polypropylene matrix composites have better energy absorption than other sample.

Park & Park (2018) aimed to compare metal automobile bonnet with NFRC bonnet, which have flax and vinyl ester components. They produced natural flax composite automobile bonnet and then tested the samples with drop weight impact machine to investigate the impact resistance. After impact test was completed, they applied the compression test on the damaged samples. The NFRC automobile bonnet displayed similar testing results with metals in terms of their compression resistance. As the determined strain, which was 54.6 mm was lower than 120 mm safety standard, the material was described as safety to use. In this work, it was demonstrated that automobile bonnets with natural flax are more safety, eco-friendly, low weight in comparison with the metal automobile bonnets.

It is possible to use NFRC with other reinforcements as hybrid composites. Thanks to the hybrid structure, the composite gains the multiple properties. For instance, while the carbon composite has ultimately higher strength and stiffness values than flax composite, it has breakable structure. Therefore, if the carbon composite is converted to the hybrid structure with the flax fiber, the final material can absorb more energy. In addition, the cost of material would be profoundly reduced.

Petrucci et al. (2015) produced hybrid composites with basalt (B), flax (F), hemp (H) and glass (G) fibers. While the basalt fibers were added to every hybrid composites, the laminates placed perpendicularly to each other. The orientations of laminates were GHB, GHB, GFB. The impact and post-impact flexural tests were applied to the materials. After tests were completed, FHB was chosen the best structure in terms of its strength value at impact test. In addition, GFB shown the highest post impact flexural resistance.

Barouni & Dhakal (2019) manufactured composites, which were reinforced by the glass , flax and glass/flax hybrid fibers. The flax and glass composites include 6-plies and laminates were placed at ±45 angles. The hybrid composite contained 7- plies and the orientation of laminates was GFGFGFG. Barouni and Dhakal used 25J and 50J energy levels for impact test. According to the test results, the hybrid composite shown better impact resistance than flax composite. Moreover, the hybrid composite has better damage tolerance than flax composite. On the other hand, the flax composite shown the best energy absorption.

Nisini et al. (2018) generated the hybrid composites with the carbon(C), basalt(B) and flax (F) fibers. These materials were named as ‘Ductile High Energy Composite (DHEC)’ by them. All composites orientation was settled as CCBFFBCC. They applied the high speed impact tests on the composites and compared all results with the pure carbon reinforced composite. While the comparisons were carried out, the different kinds of variables were fixed, which were the weight, the bending stiffness and the bending strength. After the high speed impact tests were applied, it was determined that every composite demonstrated similar energy absorption. However, the DHEC less deformed than other composites.

Wang et al. (2020) used carbon (C) and flax (F) fibers to obtain the hybrid composites. The manufactured composites include five plies and their configurations were 5C, 5F, CFFFC and FCFCF. Wangs and Xian aimed to investigate the tensile, the three-point bending, the impact and the water absorption properties of composites. According to tests results, CFFFC shown lower tensile resistance. While the 5F indicated better water absorption, FCFCF had higher energy absorption capacity in comparison with the 5C and 5F. They concluded that, if the flax fiber is getting hybrid with other type of fibers, it contributes toughness to the composite. Furthermore, the FCFCF composite exhibited maximum plastic deformation.

Papa et al. (2018) manufactured flax, basalt and flax/basalt hybrid reinforced composites. All reinforcements were woven form and they had twill structure. The impact test was applied to the all composites in the study. The impact tests were continued to penetrate the composites. Therefore, the impact behaviors of composites were examined either penetrated or non-penetrated forms. According to the force-displacement curves, the hybrid composites shown intermediate characteristics. The flax and basalt composites demonstrated similar energy absorption levels. However, the hybrid shown better energy absorption values. They observed brittle damage behavior at flax composite.

Al-Hajaj et al. (2019) used flax woven fabrics as core laminate between the twice carbon woven fabrics to obtain hybrid composite, which has 16-layers. The samples distinguished as A and B groups. The orientations of groups were settled as cross-ply and bidirectional. Al-Hajaj and friends carried out impact tests from 5J to 40J energy levels. According to experimental results, they aimed to examine energy absorption, damage evaluation and crack length, indentation depth, thermographic imaging and impact strength of materials. While both groups shown similar energy absorption, A type and B type composites penetrated at 37J and 40J energies, respectively.

Ricciardi et al. (2019) generated hybrid composites from flax (F) and basalt (B) fabrics, which have twill types. The samples have 16- layers and were named as N.1 (BFBBFBFFFFBFBBFB), N.2 (BBFFBBFFFFBBFFBB) and N.3

(BFBFBFBFFBFBFBFB). They applied the shear, the flexural and the impact tests to the materials. While the N.3 had better shear resistance, N.2 indicated lower young modulus for flexural test. The impact tests were carried out at 15J, 30J and 40J energy levels. Besides, while the N.3 had best impact resistance value, the N.2 shown largest damage area. On the contrary, the N.2 demonstrated best energy absorption.

Bar et al. (2020) obtained the hybrid composite materials with the polypropylene and the flax fabrics. Two types of fabrics were used in the study, which were woven and unidirectional. The woven fabric had plain structure. The behaviors of samples were investigated under the low velocity impact load. The samples were flax-pp-pw, flax-pp-ud and glass-pp-ud. Afterwards the tests were finished, it was found that the most energy absorbed material was glass-ud. Furthermore, flax-pp-pw had better energy absorbed than flax-pp-ud. The glass-pp-pw shown best impact resistance and flax-pp-ud demonstrated worst under impact load.

Nisini et al. (2017) manufactured two types hybrid composites with carbon(C), basalt(B) and flax(F) fibers. The laminates of composites had N.1 (CCBFFFFBCC) and N.2 (CCFBFFBFCC) stacking sequences. They carried out the tensile, the three-point bending, the inter-laminar shear strength and the falling weight impact tests. When the results were compared with pure flax, basalt or glass composites, hybrids shown better mechanical properties except impact tests. In addition to this, N.2 shown better mechanical properties than the N.1.

Gowda et al. (2021) used hybrid composites, which included the flax(F), the basalt (B) and the carbon(C) fabrics. The epoxy(E) or bio-epoxy(BE) matrixes were chosen to produce composites. The samples were named as C1:(FFFF-BE), C2:(FFFF-E), C3:(CFFC-BE), C4:(CFFC-E), C5:(BFFB-BE), C6:(BFFB-E). At the same time, Gowda et al. applied the tensile, the flexural, the inter-laminar shear strength and the impact tests to the composites. After the test results were examined, they observed that C3 and C6 shown the best flexural and impact resistances, respectively. Moreover, the composites, which were produced with bio-epoxy, demonstrated the best water absorption.

Fragassa et al. (2018) produced pure flax, basalt and flax/basalt hybrid composites. Then, the tensile, the flexural and the falling weight impact tests were applied to the samples. It was found that the flax demonstrated more linear tensile stress-strain curve. The hybrid shown average values between the flax and the basalt composites. On the other hand, the flax behaved less brittle when it converted to the hybrid with the basalt fiber.

Although NFRC have lower strength or stiffness values than synthetic fiber reinforced composites, they have specific properties and exhibit couple of advantages. When their behaviors are compared with the synthetic reinforced composites, the differences are better distinguished.

Wang et al. (2020) generated composites with the plain concrete (PC) matrix. The flax (F) and the glass (G) fibers were used as reinforcements. The samples were pure PC, the flax fiber reinforced (FFRP-PC) and glass fiber reinforced (GFRP-PC). The static compression and the impact tests were implemented to the composites. While the PC directly crushed under the compressive load, GFRP-PC had better compression strength results than other materials. GFRP-PC shown highest impact resistance and PC had lowest impact resistance value.

Frydrych et al. (2020) produced the flax reinforced, the basalt reinforced and non-reinforced geo-polymer composites. They compared the results of samples with the synthetic composites results. They analyzed the impact bending, the bending strength and the compressive strength of the materials. Finally, they determined that the flax reinforced composites shown better impact bending resistance than basalts. Moreover, it was concluded that the natural fiber reinforced composites shown better impact bending and strength values than non-natural fiber reinforced composites.

Baley et al. (2016) manufactured the unidirectional flax and the e-glass reinforced composites. While the matrix easily moved among the e-glass fibers, it hardly penetrated inside of the flax fibers. Besides, the flax reinforced composites have lower shear rigidity values than e-glass reinforced composites. Also, it was determined that the flax reinforced composite was more brittle than the e-glass reinforced composite. The e-glass composite was the best in-plane shear strength values. However, the flax reinforced composite shown lower fracture potential due to the its lower in- plane shear strength.

Chilali et al. (2016) generated composites with flax and glass woven fabrics, which have twill structures. They used thermoplastic (elium) and thermoset (epoxy) matrixes to produce materials. Chilali et al. applied the tensile tests at bias (45˚) and warp directions. The samples were FFR (flax reinforced)-Epoxy, FFR-Elium, GFR (glass reinforced)-Epoxy and GFR-Elium. It was determined that the thermoplastic composites had more ductile behaviors. When the epoxy and elium matrixes were compared, the epoxy had better strength values. In addition to this, it was seen that the glass composite shown better strength values than flax composite. FFR-Elium has also higher shear modulus value than FFR-Epoxy.

Bensadoun et al. (2017) produced different flax reinforced composites by the types of reinforcements, which were random mat, plain woven, twill woven, unidirectional and quasi unidirectional. Moreover, the composites were diversified in terms of the matrix materials, which were thermoset (epoxy) and thermoplastic (MAAP). It was detected that the thermoplastic composites could absorbed 50% more energy than thermoset composite.

The additive materials can cause to change the mechanical behaviors of composites as well as the type of reinforcements or matrix materials. Therefore, lots of the studies have focused on the additives for composites in the last decades.

Laziz et al. (2020) treated composites with polylactic acid (PLA) and analyzed their mechanical behaviors. PLA treated composites grouped as wet or dry treated PLAs. In addition, some of PLA composites' flax fibers treated with NaOH. The flexural and low velocity impact tests were applied to the produced composites. Wet PLA composite indicated higher resistance than dry PLA composite at three-point bending test. Moreover, NaOH treated composite shown better flexural strength value than non-treated composites. In addition, treated composites had better values at either impact or bending behaviors. The authors concluded that the alkaline improve the impact resistance of composites.

Matykiewicz & Barczewski (2020) manufactured hybrid composites with flax and basalt fibers. Hybrid composites were taken placed from four plies basalt and two plies flax layers. The samples were differentiated with the basalt powder, which was applied to the matrix. The thermogravimetric analysis (TGA) in inert and oxidizing atmospheres and dynamic mechanical thermal analysis (DMTA) were carried out. In addition, the tensile, the flexural tests and the impact tests were applied to the materials. The modified composites lost lower values of flexural modulus and it indicated the best flexural resistance value.

Baley et al. (2018) produced composites from the flax and jute fibers. In addition, they diversified materials according to the matrix types, which were polypropylene (PP), maleic anhydride grafted PP (MAPP), polyamide 11 (PA11), acrylic and epoxy. Baley et al. performed the tensile and the compression tests to the composites. It was determined that if the MAPP is added to the PP composites, the tensile and shear properties increase. The flax-epoxy composites shown better tensile and compression stiffness than jute-epoxy composites. Furthermore, it was found that the PP and acrylic composites had worst interfacial shear strength.

Le Duigouet al. (2016) obtained natural reinforced composites from flax and polyamide 11. The shear tests were carried out on the samples and results were compared with other natural composites results from the literature. The samples shown better shear stiffness values than other natural composites. On the other hand, the composites, which have polyamide 11 matrix, had lower shear rigidity value. They were shown that composites with polyamide 11 improved interfacial properties of natural composites.

Cerbu (2015) manufactured 8-layered flax reinforced composites. Cerbu investigated mechanical properties of composites at either warp or weft directions. The impact, the tensile and the flexural tests were applied to the composites. It was aimed to detect young's modulus, stress values, strain values and strengths values of samples. It was concluded in the study that the composites shown better mechanical properties at weft direction than warp direction in tensile and flexural tests.

The materials, which are produced for structural applications, are mostly subjected to the impact load in their usage area. Therefore, a number of studies were carried out to investigate the behavior of natural fiber reinforced composites under the impact load.

Habibi et al. (2018) produced flax reinforced composites and investigate their behavior under impact load. The impact tests were verified with respect to the impactor shapes. They applied low velocity impact tests at six different energies (4J, 6J, 8J, 10J, 12J, 14J), which were carried out with hemispherical and conical impactors, separately. The analyzed composites were delaminated at 14J, when the impact test was applied with hemispherical striker. If the striker was changed with the conical, the perforation was observed at 10J energy level. After they analyzed the penetration depth, it was determined that the penetration depth of conical impactors was larger than hemispherical strikers' penetration depth.

Habibi et al. (2020) manufactured flax composites and the impact tests implemented to them at 1J, 2J, 3J, 4J, 5J energy levels. Furthermore, the impact tests applied to the materials at different angles, which were 15˚, 30˚, 45˚ and 60˚. While any cracks were not observed at 30˚ and 15˚ angles, the cracks began to occur at 45˚ and 60˚.

The compression is one of the significant mechanical tests to characterize the materials' behaviors. Hence, many of the studies were carried out to examine the compression behavior of NFRC as well as the tensile, the bending, the shear and so on.

Hu et al. (2018) produced flax reinforced composites and applied dynamic loading tests at its warp directions. The material contain 20-layers and epoxy matrix was used. The testing graph of composite has linear-elastic section at beginning stage. Then, the increasing of load values was gradually decreased and finally, toughness phase was observed. In addition, it was detected that the mechanical behavior of materials, which were tested with dynamic loading tests, depended on the testing speed.

Composite materials can show the different mechanical behaviors according to the types of reinforcement. Nowadays, woven reinforcements are mostly preferred to produce polymer composites for structural applications. At the same time, the fabric architecture is a significant factor to characterize to mechanical behavior of composites.

Duc et al. (2014) produced flax fabrics reinforced composites, which have different fabric architectures. The composites were reinforced by unidirectional fabric (UD), twill fabric (TW) and 0/90 stacking sequences. They were aimed to analyze mechanical and dynamic mechanical analyses properties of the samples. Tests results shown that the stiffness of flax fabrics composites were negatively affected by the twisted yarns. However, the twisted yarns increased the dynamic mechanical properties of composites. Moreover, the twill woven fabric reinforced composites have low young's modulus because of the twisted yarns which consisted the crimp. It was concluded in the study that the flax fibers improved the dynamic mechanical properties and stiffness results thanks to their less dislocations.

Ravandiet al. (2017) stitched the flax fabrics and converted to them the composite materials. They examined impact behaviors of materials. The sample groups were non-stitched (PW0), cotton stitched (PWC), flax stitched (PWF) and unstitched cross-ply $[0/90]_{4s}$. The low velocity tests were applied to the materials till they were perforated. Hence, their non-perforated and perforated energy levels were profoundly analyzed. It was found that the stitched composites indicated larger crack length because the stitching cause to defects like fiber breakage, waviness and crimping of in-plane fibers.

Liu & Hughes (2008) manufactured flax composite materials and differentiated to them by means of the yarn densities, woven types and stacking sequences. The tensile test was applied to the materials to examine the fracture behavior and fracture toughness of samples. When the yarns density was increased in the reinforced fabric, it was observed that the strength and stiffness of composites were increased. In addition, all composites shown better fracture toughness at weft direction than warp direction.

CHAPTER TWO

MATERIALS AND METHOD

2.1 Materials

2.1.1 Flax Fabric Properties

2.1.1.1 Flax Yarn Properties

The flax yarns were supplied from the Nil-As Keten, Istanbul, Turkey. The yarn has 4.8 Nm linear density and 100 % flax content. The yarns have 300 twists per meter, which is optimal value to weave yarn without fiber breakage or yarn- machine friction damage.

2.1.1.2 Production of Flax Woven Fabrics

The fabric production was begun the warping process. The yarns were transferred from bobbin to the warp beams by means of the warping machine, which is shown in Figure 2.1.

Figure 2.1 The warping machine

After the warping process was completed, the drawing process was carried out to pass every yarn from the heddle eyes. Totally four heddle frames were used to produce fabrics. The drawing process, heddle frames and yarns are shown in Figure 2.2.

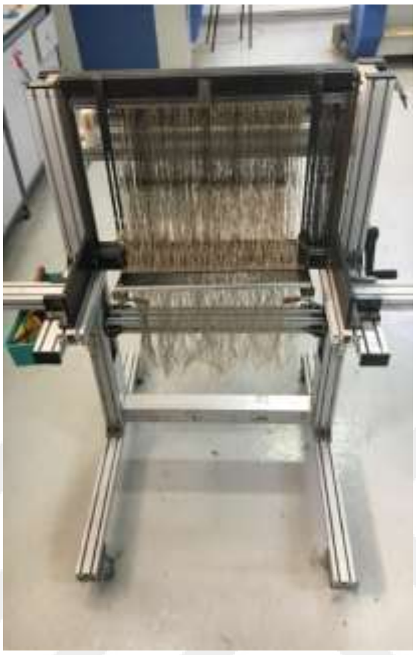


Figure 2.2 The heddle frames and the yarns

The fabrics were produced from the flax yarns by automated weaving machine, which is CCI Tech Evergreen II and is in the weaving atelier of Textile Engineering Department of Dokuz Eylül University. The weaving machine is shown in Figure 2.3.

Figure 2.3 The weaving machine

The 1x3 twill structure was chosen to produce fabric, which were reinforced the composites. All fabrics include 10 warp yarns per cm. The fabrics were obtained with 160 x 40 cm dimensions as shown in Figure 2.4.

Figure 2.4 The flax fabric

The fabrics were diversified according to the weft yarn densities, which are 6, 8 and 10 yarns per cm, and their all warp densities were settled to 10 yarns per cm. All types of fabrics are presented in the Figure 2.5.

Figure 2. 5 All types of fabrics

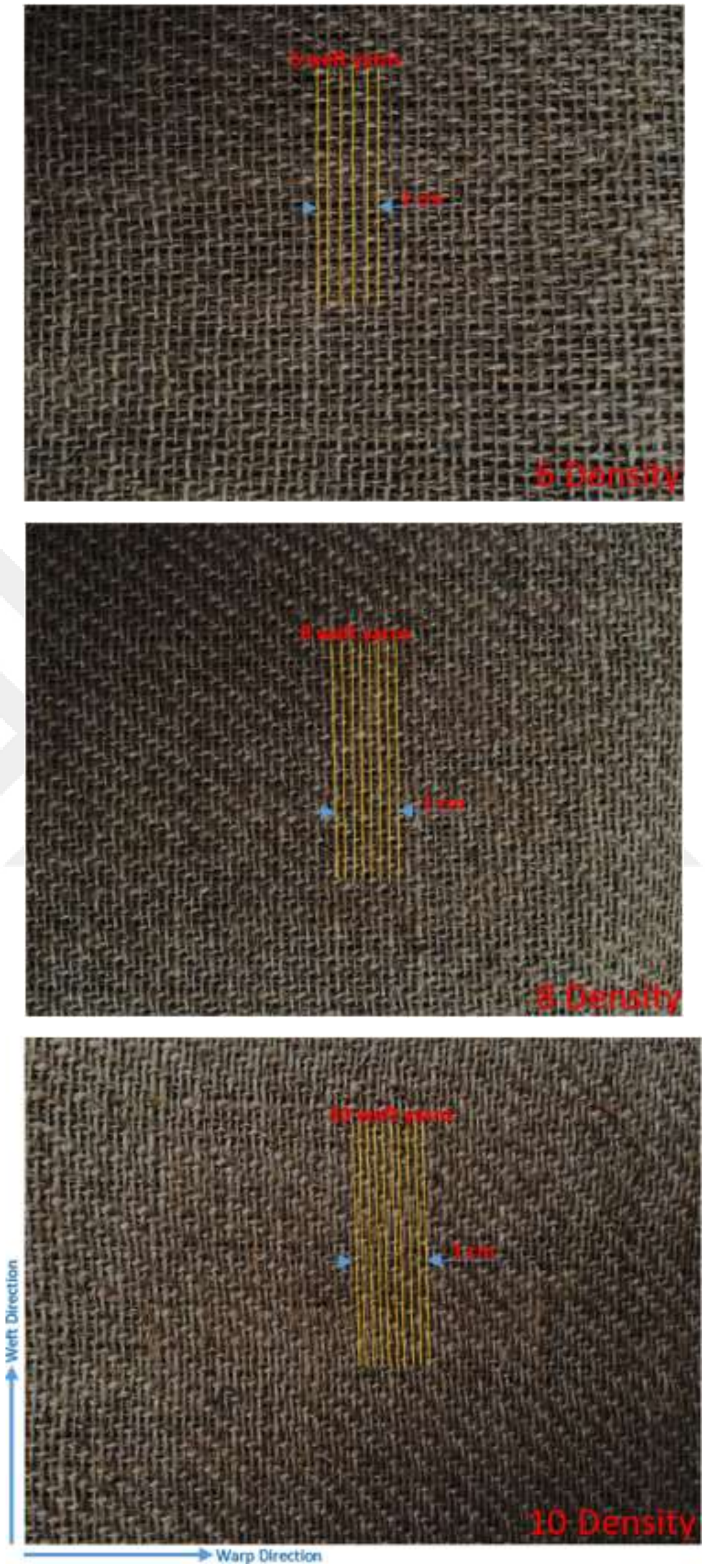


Figure 2. 5 All types of fabrics

2.1.2 Epoxy Properties

F-1564 coded epoxy resin was used to produce composites. The resin and hardener belong to the Fibermak Composites, Izmir, Turkey. While the resin has 1.15 g/cm³ density at 25ºC, the hardener, which is F-3487 coded, has 1 g/cm³ density at 25ºC.

2.1.3 Production of Flax Woven Fabric Reinforced Composites

The composite materials were manufactured with the vacuum assistant resin transfer method in the composite laboratory, Mechanical Engineering Department, Dokuz Eylül University.

In this work, the hardener to resin proportion was settled as 1/3. The prepared epoxy matrix was added to the fabrics by aid of the vacuum. The process was continued until every point of fabrics was getting wet by the resin. Afterwards, the material was waited for curing process. The composite production system is shown in Figure 2.6.

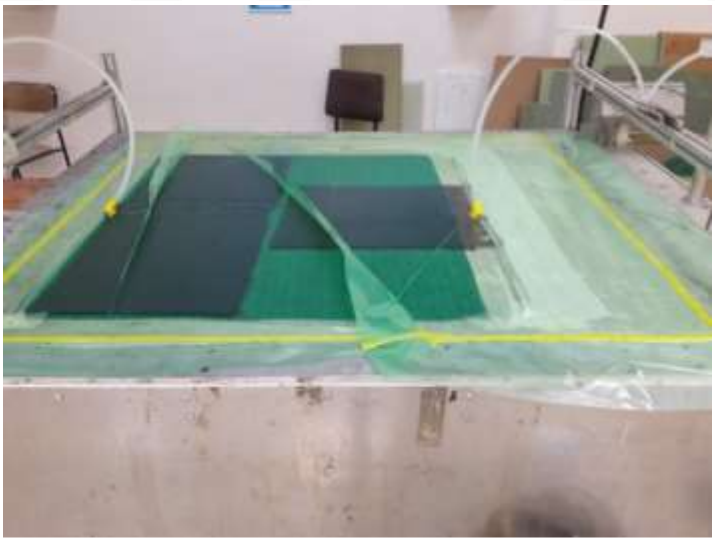


Figure 2. 6 The composite production system

The curing process was applied to the samples at 80º C, throughout 8 hours. After the production of composites were completed, the testing samples were prepared according to the testing ASTM standards. The wet cutting saw was used to cut the composite panels (Figure 2.7).

Figure 2.7 Wet cutting saw

2.2 Method

2.2.1 The Structural Properties of Flax Yarns and Woven Fabrics

2.2.1.1 The Determination of Areal Weigh of Fabrics

ISO 12127 test standard was followed to measure the areal weight of flax woven fabrics.

2.2.1.2 The Determination of Crimp Percentages of Yarns

ISO 7211-3 test standard was followed to measure the crimp percentages of warp and weft yarns of flax woven fabrics.

2.2.2 Mechanical Tests for Composite Materials

Since the mechanical behaviors of materials could be determined, the mechanical tests were applied to the composites. Therefore, the tensile, the compressive and the shear tests were carried out to characterize the mechanical behaviors of flax fabric reinforced composites. Furthermore, the impact test was applied to all samples. In this section, all mechanical tests were applied to the composites, which have 3-layered flax woven reinforced for every weft density. The thicknesses of composites were $t_{6\ density}$: 2.7mm, $t_{8\ density}$: 2.8mm and $t_{10\ density}$: 2.9mm.

Table 2.1 The symbols and their explanations

Symbol	Explanation
P	Force (N)
A	Cross-section area (mm^2)
σ_1, σ_2	Tensile stress in warp and weft directions (MPa)
σ_c	Compressive stress (MPa)
E_1	Modulus of elasticity in warp direction (MPa)
E_2	Modulus of elasticity in weft direction (MPa)
ν_{12}	Poisson’s ratio
ε_1	Strain in warp direction
ε_2	Strain in weft direction
τ_{12}	Shear stress (MPa)
G_{12}	Shear modulus (MPa)
γ_{12}	Shear strain

2.2.2.1 Tensile Test

The tensile behavior is one of the significant mechanical properties of materials. Tensile strength, modulus of elasticity and Poisson’s ratio values of composite materials could be determined by the tensile test.

In this study, the tensile load is applied to the flax reinforced composites according to the ASTM-D3039/D3039M-14. The five samples were prepared at warp and weft directions. The dimensions of the samples were 15mm x 250mm at warp direction and 25mm x 175mm at weft direction. The both samples are shown in Figure 2.8.

Figure 2.8 The tensile test samples for warp and weft directions

The tensile tests were carried out by Shimadzu Autograph AG-X 100 kN tensile test machine in Department of Mechanical Engineering, Dokuz Eylül University (Figure 2.9).

Figure 2.9 Shimadzu Autograph AG-X tensile test machine

While the tensile load was measured by the machine, the tensile strains of samples were measured by the machine, extensometer and the strain gage. The measuring system of extensometer is shown in Figure 2.10.

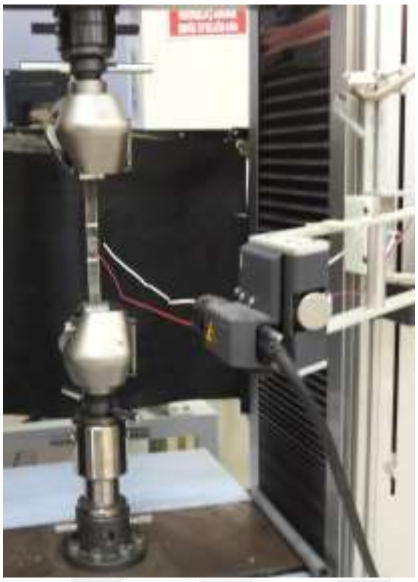


Figure 2.10 The measuring system of extensometer

At the same time, Poisson’s ratio and modulus of elasticity of samples are obtained by the strain-gage, which were placed in both warp or weft directions. TDS-530 data logger was used to obtain measuring strain values as shown in Figure 2.11.

Figure 2.11 The strain-gage data logger

After the tensile tests, the following formulations are used to determine E_1, E_2 and υ_{12}.

$$\sigma_1 = \frac{P_1}{A} \tag{2.1}$$

$$E_1 = \frac{\sigma_1}{\varepsilon_1} \tag{2.2}$$

$$\nu_{12} = -\frac{\varepsilon_2}{\varepsilon_1} \tag{2.3}$$

$$\sigma_2 = \frac{P_2}{A} \tag{2.4}$$

$$E_2 = \frac{\sigma_2}{\varepsilon_2} \tag{2.5}$$

2.2.2.2 Compression Test

The compressive strength, stiffness and strain properties of materials were determined with the compressive test. The compressive test was applied to the materials via the Shimadzu Autograph AG-X 100 kN tensile test machine. Combined loading compression test apparatus was used to carry out compression test according to the ASTM-D6641/D6641M-09 standard as shown in Figure 2.12.

Figure 2.12 Combined loading compression test apparatus

In the compression test, five samples were prepared to test for every type of structure in both directions. The equation 2.6 was used to calculate the compressive strength.

$$\sigma_c = \frac{P}{A} \tag{2.6}$$

Samples with dimensions of 13 mmx140 mm were prepared for compression test in warp or weft directions. (Figure 2.13).

Figure 2.13 The compressive test sample

2.2.2.3 Shear Test

The V-Notched Rail shear test was applied to the materials to obtain shear strength and shear modulus of composites according to the ASTM-D7078/D7078M-19 standard. The shear test setup is shown in Figure 2.14.

Figure 2.14 The shear test setup

The Shimadzu Autograph AG-X 100 kN tensile test machine was used to carry out shear tests. The shear test sample and its dimensions are given in Figure 2.15.

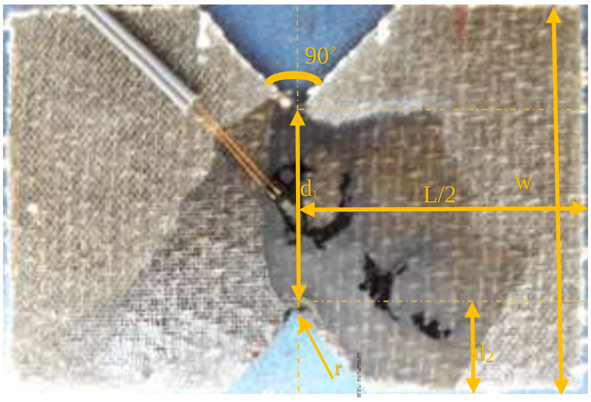


Figure 2.15 The shear test sample and its dimensions (d1=31mm, d2=12,7mm, w=56mm, L=76mm, r=1.3 mm)

In the shear test, five samples were prepared for every type of composites. The strain gage was settled on the samples at 45˚ angles to obtain shear strain values. Shear strength and shear modulus were calculated by using equations (2.6) and (2.7), respectively.

$$\tau_{12} = \frac{P}{A} \tag{2.6}$$

$$G_{12} = \frac{\tau_{12}}{\gamma_{12}} \tag{2.7}$$

2.2.3 Low Velocity Impact Test

The impact tests were carried out according to the ASTM D5628-18 standard. The all low velocity impact tests were applied thanks to the CEAST Fractovis Plus impact machine and hemispherical striker was used. The machine is shown in Figure 2.16.

Figure 2.16 The low velocity impact machine

In addition, the samples were cut at 100mm x 100mm dimensions by the wet cutting saw and they were produced with 12-layer flax woven laminates. The thicknesses of composites were $t_{6\ density}$: 13mm, $t_{8\ density}$: 13.4mm and $t_{10\ density}$: 13.8mm. A sample, which was damaged by the impact load, is shown in Figure 2.17.

a) b)

Figure 2.17 The low velocity impact test sample, a) front face, b) back face

The tests were applied at 50 J, 75 J and 100 J energy levels. Furthermore, the impact tests were repeated three times for every energy level.

CHAPTER THREE

RESULTS AND DISCUSSION

3.1 The Flax Fabrics Measurement Results

3.1.1 The Results of Fabric Areal Weights

While the flax fabric, which has 10 weft density, has 439.39 g/m², the areal weight values of fabrics, which have 8 and 6 densities, were measured as 395.87 g/m² and 336.1 g/m², respectively.

3.1.2 The Results of Yarn Crimp Percentages

The results of crimp percentage measurement of yarns are shown in the Table 3.1.

Table 3.1 The crimp percentage values of yarns for flax fabrics

6 Density		8 Density		10 Density	
Warp	Weft	Warp	Weft	Warp	Weft
4.94%	2.25%	5.25%	4.19%	7.32%	4.05%

3.2 Test Results

The flax woven fabrics, which have different number of weft densities, were produced and converted to the composites in this work. The composites were mechanically characterized by means of the tensile, the compressive and the in-plane shear tests. Moreover, the low velocity impact test was applied to examine their behaviors. The laminates of all composites were oriented at 0°. While the tests, which were used for mechanical characterization, were applied to 3 layers of flax reinforced composites, the impact test was implemented to the 12 layers of flax reinforced composites. All tests results are presented at this section of thesis.

3.2.1 Results of Tensile Tests

The tensile tests were performed on the samples in warp and weft directions to determine the tensile properties.

3.2.1.1 Results of Tensile Tests in Warp Direction

After the tensile tests were completed, the stress-strain graphs were obtained from the machine. The stress-strain graphs of samples with 6-weft densities in warp direction are shown in Figure 3.1.

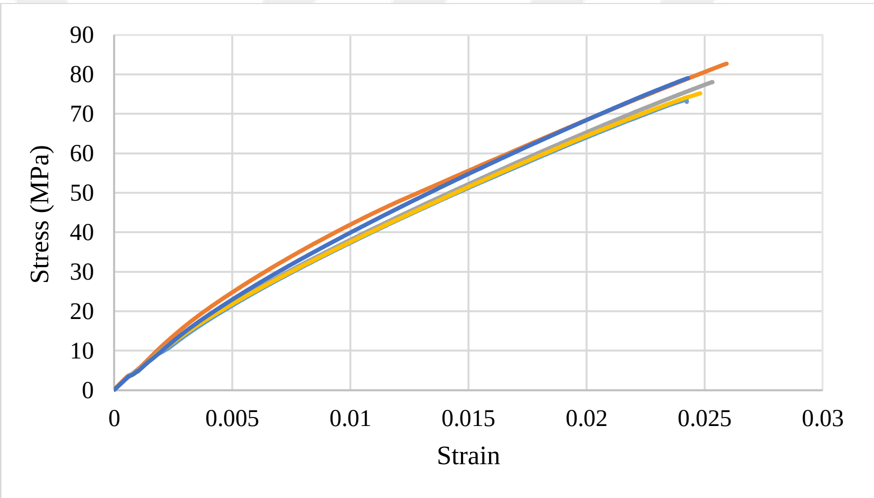


Figure 3.1 Stress-strain graphs of samples with 6-weft density in warp direction

The average tensile strength values of composites, which have different weft densities, are presented in Figure 3.2. When the number of weft densities increases in the fabric, the tensile strength values decrease in the warp direction. The crimp percentage of warp yarn raises linearly with the number of weft density. Therefore, the tensile strength value decreases because of the crimp percentage.

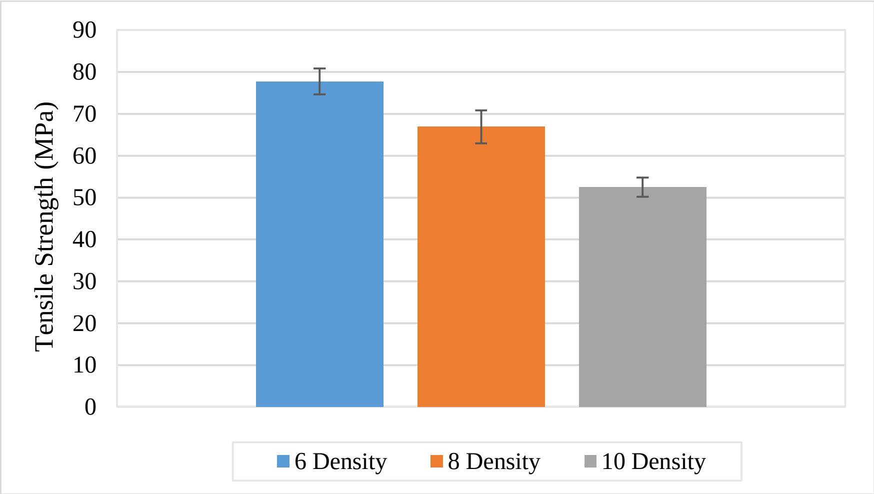


Figure 3.2 Tensile strength values of composites in the warp direction

The strain values were determined with different methods, strain gage, extensometer and the data from the tensile machine. Modulus of elasticity was calculated with strain values from above methods for every density and then compared to each other. The different modulus of elasticity values were calculated as shown in Figure 3.3.

It was determined that if the number of weft density is increased in the fabric, the elastic modulus is decreased at warp direction. It is seen in the graph that the distinct elastic modulus values were obtained from the measuring methods. The extensometer and machine values would be affected by the environmental factors such as lights or unstable apparatus. On the other hand, the closest values with the results, which is in the literature, were obtained by strain-gage.

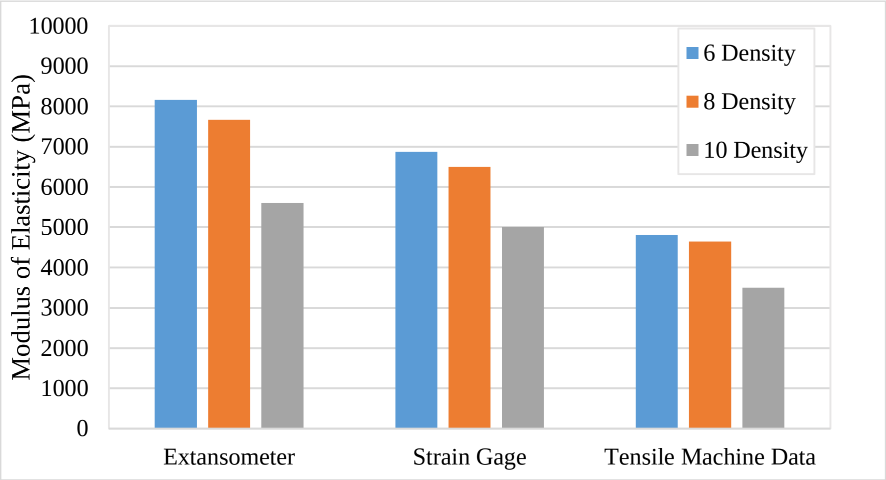


Figure 3.3 Modulus of elasticity in warp direction according to the different measuring methods

Poisson's ratio was obtained by the two-way strain-gage. It is seen in the graph that the composites have various Poisson's ratios to each other. If the weft density is increased in the fabric, the composites have higher Poisson's ratio values at warp direction.

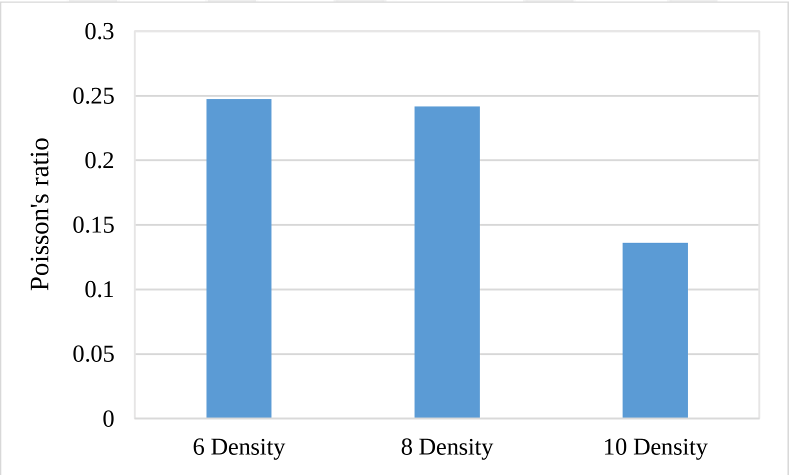


Figure 3.4 Poisson's ratio values of composites

3.2.1.2 Results of Tensile Tests in Weft Direction

It was aimed in the study to investigate modulus of elasticity and tensile strength of composites in weft direction as well as warp direction.

Tensile strength values of composites are shown in Figure 3.5. While tensile strength values in warp direction have inverse relationship with the number of weft densities, tensile strength values in weft direction is proportionally raised with the number of weft density.

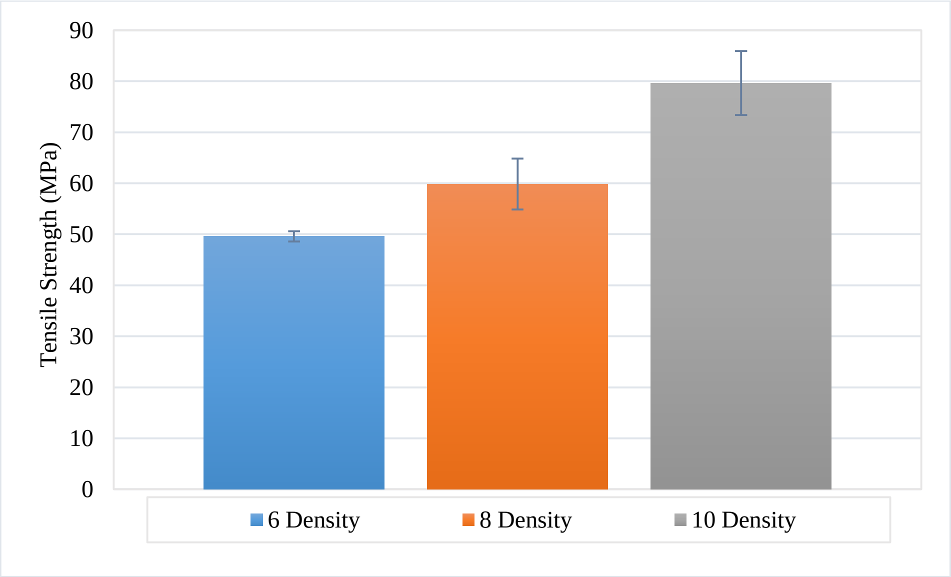


Figure 3.5 Tensile strength values of composites in weft direction

The elastic module values of composites for weft direction is presented in Figure 3.6. It can be seen in the graph that the elastic modulus of composites is linearly increased with the number of weft densities.

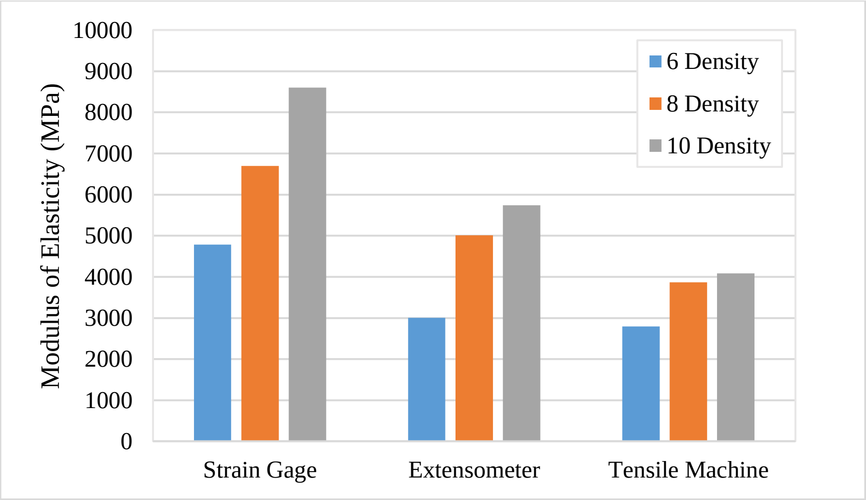


Figure 3.6 Modulus of elasticity in weft direction according to the different measuring methods

3.2.2 Results of Compression Tests

The compression tests were carried out to investigate the maximum compressive strength of our samples and compared to each other for different weft densities.

3.2.2.1 Results of Compression Tests in Warp Direction

Compression tests were applied to five samples for both directions of every type composite. The stress-strain graphs of composite with 8-weft density in the warp direction is shown in Figure 3.7.

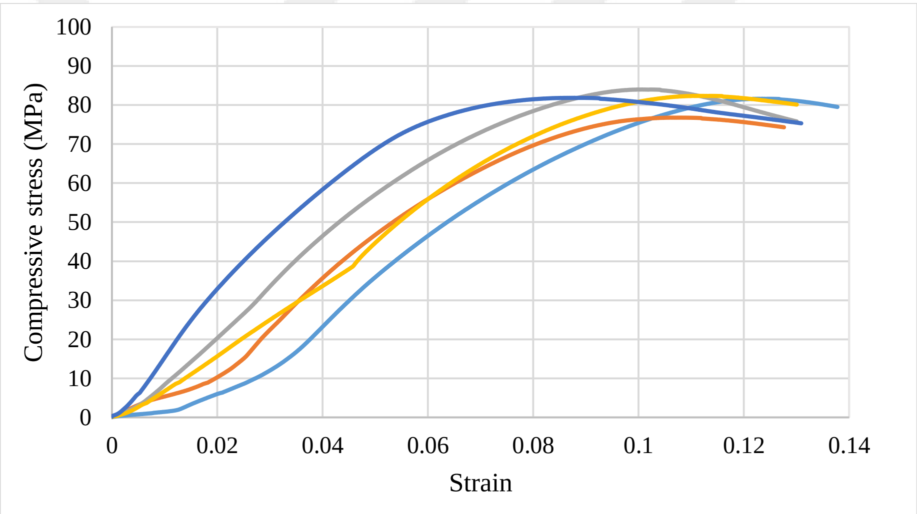


Figure 3.7 Compressive stress-strain graphs of composites with 8-weft density in warp direction

Compressive strength values are given in Figure 3.8. It is seen in the graph that the values are varied between 58.12 MPa and 62.8 MPa. The statistically meaningful differences were not obtained among the compressive test results in warp direction.

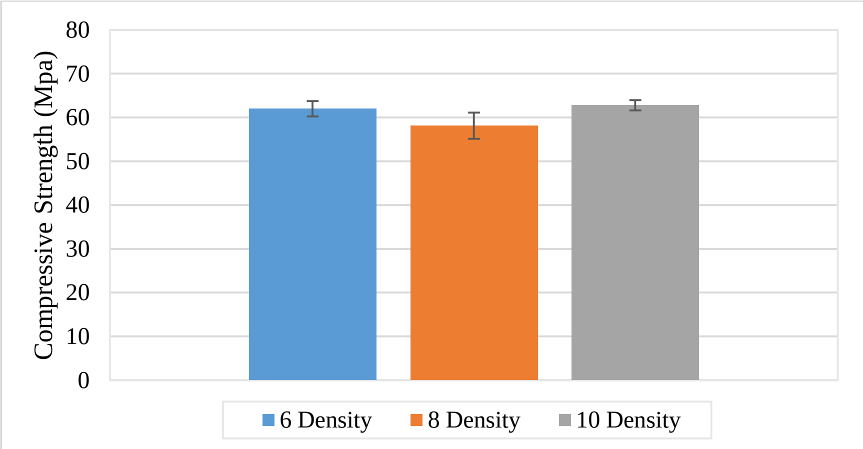


Figure 3.8 Compressive strength of composites in the warp direction

3.2.2.2 Results of Compressive Tests in Weft Direction

Compressive strength values of composite in weft direction is shown in Figure 3.9. While the 6-density flax reinforced composites and 8-density flax reinforced composites demonstrated similar compressive stress value, the 10-density flax reinforced composites shown highest stress value. Indeed, the increasing number of yarn density affected the compressive strength of composite in the weft direction, but this differences is not a distinguishable as much as in the tensile strength results.

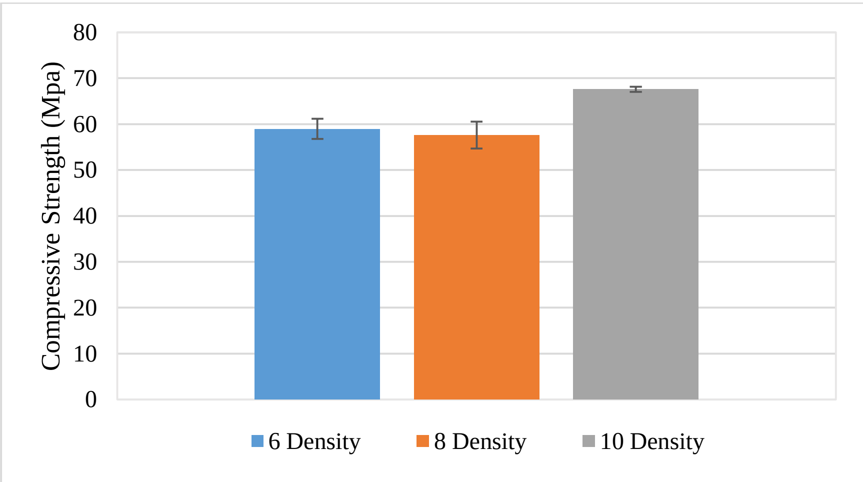


Figure 3.9 Compressive strength of composites in the weft direction

3.2.3 Results of Shear Tests

The shear tests were applied to the composite for investigating the maximum shear stress and the shear modulus values. The shear strain values of samples were obtained via the strain gages.

Shear strength values of composites are presented in Figure 3.10. It is seen from this figure that the different weft densities did not affect the shear strength results.

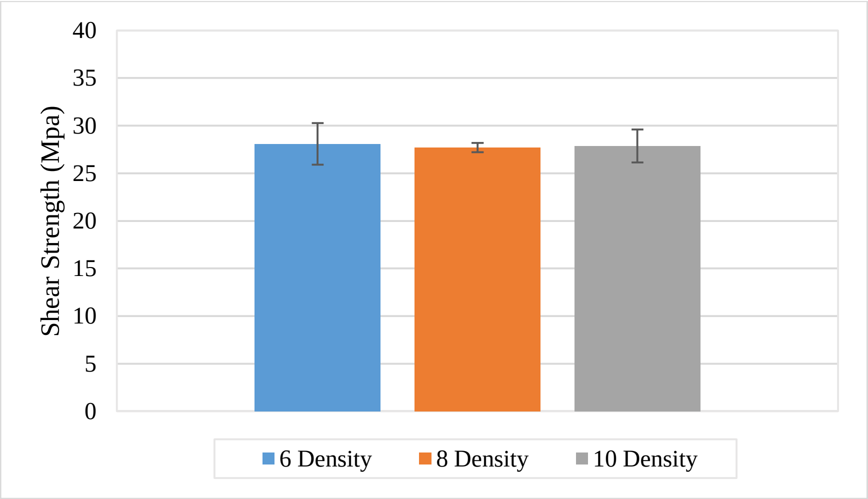


Figure 3.10 Shear strength of composites for different densities

The shear modulus values are shown in Figure 3.11. It is seen from the graph that shear modulus values have inverse relationship with the number of weft densities.

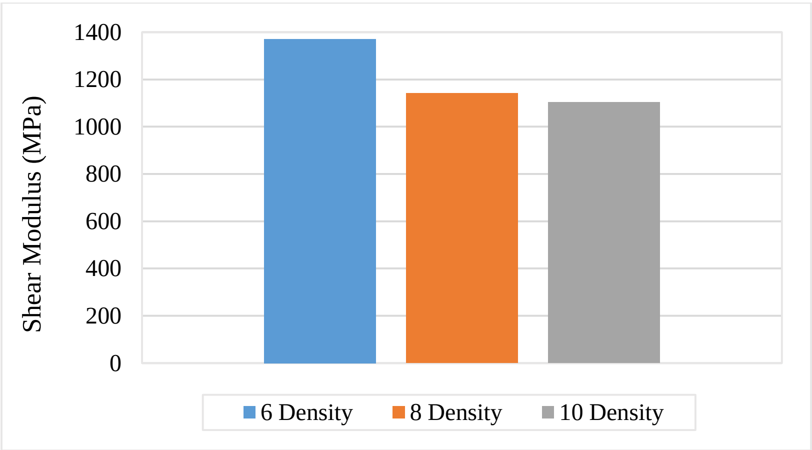


Figure 3.11 Shear modulus of composites for different densities

3.2.4 Results of Low Velocity Impact Tests

The low velocity impact tests were applied the composites to investigate the composites' damages, impact strength and absorbed energies.

The cracks were formed on the samples in 50 J while they were totally perforated in 100 J. Moreover, the test results demonstrated that 75 J is the limit of composites to begin the perforating.

After the low velocity impact tests were carried out, the contact force-displacement graphs were obtained for different densities as shown in Figure 3.12. Although the composites, which are 8 and 10 weft densities, were shown similar contact force values, the values of 6 density composite were diversified. It was concluded that if the weft density is increased in the natural fiber reinforced composite, the material behaves more stable.

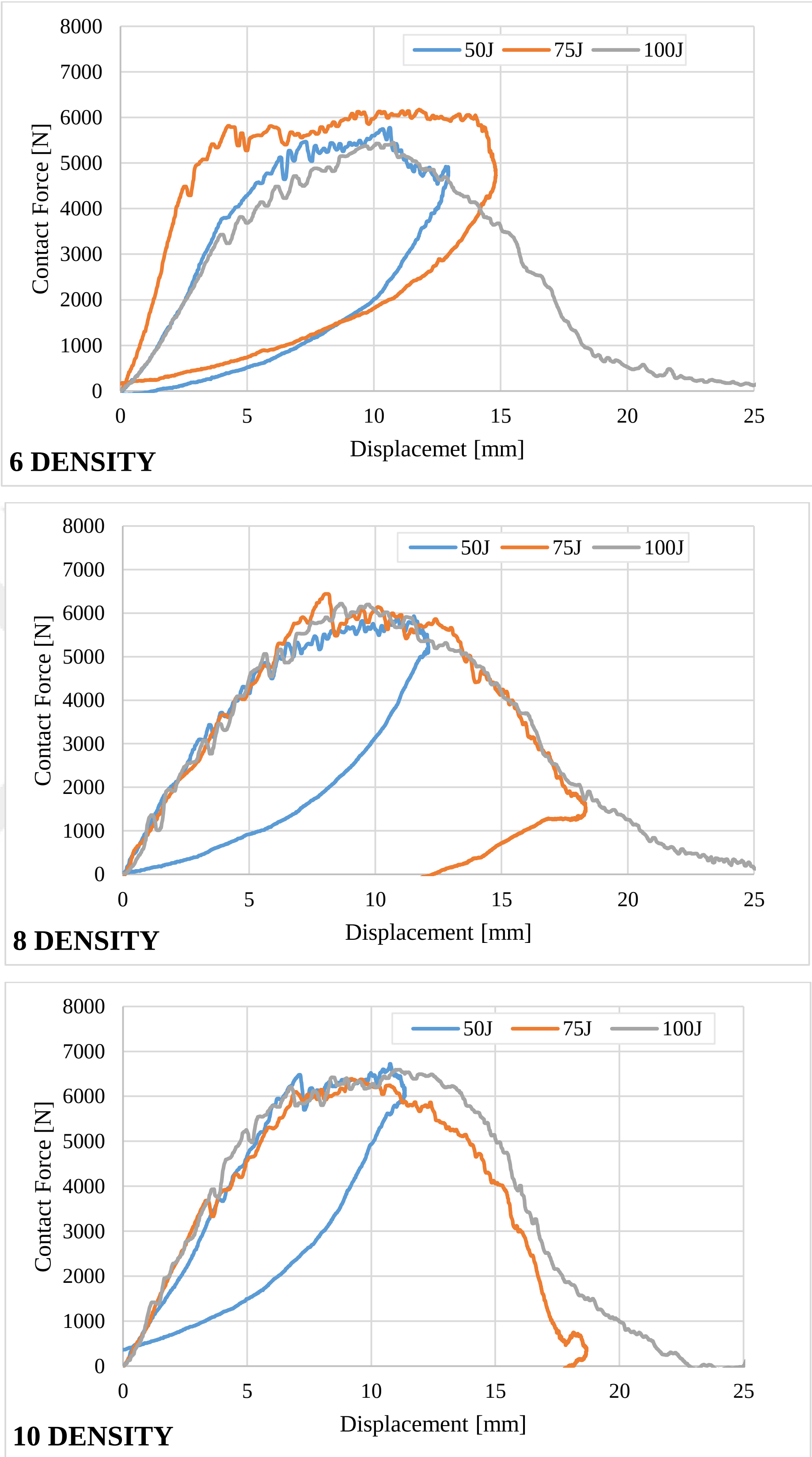


Figure 3.12 Contact force-displacement graphics according to the impact energy for different densities

Contact force-displacement graphs for different energies are shown in Figure 3.13. It was determined that the contact force values were increased with the weft density values of composites.

Figure 3.13 Contact force-displacement graphics according to the density for different impact energies

The face and back surfaces of damaged impact test samples are shown in the Table 3.2. While the crack length is increased with the impact energy level, it has inverse relationship with the number of weft density. Furthermore, the contact force values of composites, which were under the 100 J impact energy, were raised with the number of weft density. The rebounding was observed in 50J and 75J energy levels for every composite. However, the 8 and 10 densities composites were close to perforation in 75J energy level.

Table 3.2 The face and back surfaces of damaged impact test samples

	6 Density		8 Density		10 Density	
	Face	Back	Face	Back	Face	Back
50 J						
75 J						
100 J						

On the other side, the delamination of composites were observed at different impact energy levels. The 8 weft density composite's cross sections are presented in the Figure 3.14. The delamination was observed in the composite at 50 J impact energy level. Additionally, the size of delamination was raised in 75J as it can be seen in the Figure 3.14 (b). It was verified that the composite completely delaminated in 100 J energy level.

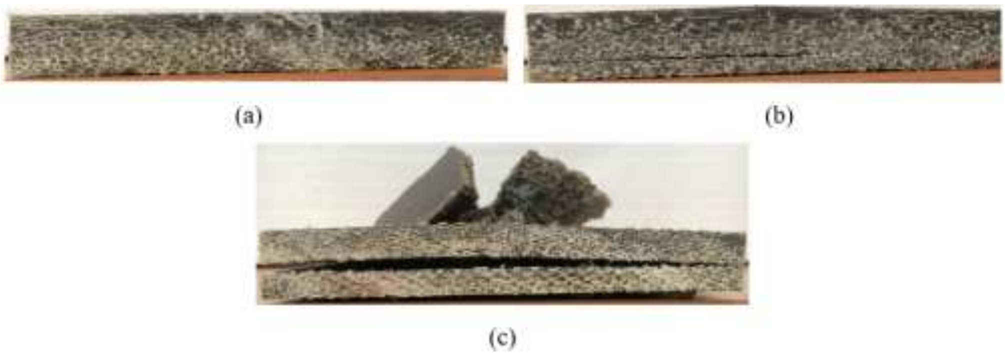


Figure 3.14 The delamination problems on the damaged impact test samples a) impacted at 50 J, b) impacted at 75 J, c) impacted at 100 J

Contact force/energy-time graphs for different densities are presented in Figure 3.15. The energy absorption values of samples were proportionally increased with the energy level. In addition to this, the bending stiffness of composite is raised as long as the energies were increased.

Contact force/energy-time graphs for different energies are given in Figure 3.16. The 6, 8 and 10- densities samples demonstrated more similar bending stiffness values in 50 J energy level than 75 J and 100 J energies. However, it can be seen from the figure that the 6-density composite had highest energy absorption value in the 50J when it was compared with 8 and 10 densities. On the contrary, 10 density composite has highest energy absorption value in 100 J energy level.

It was concluded that while the energy absorption capacity of flax reinforced composite is linearly raised with the number of weft density, they have inverse relationship for low energy levels.

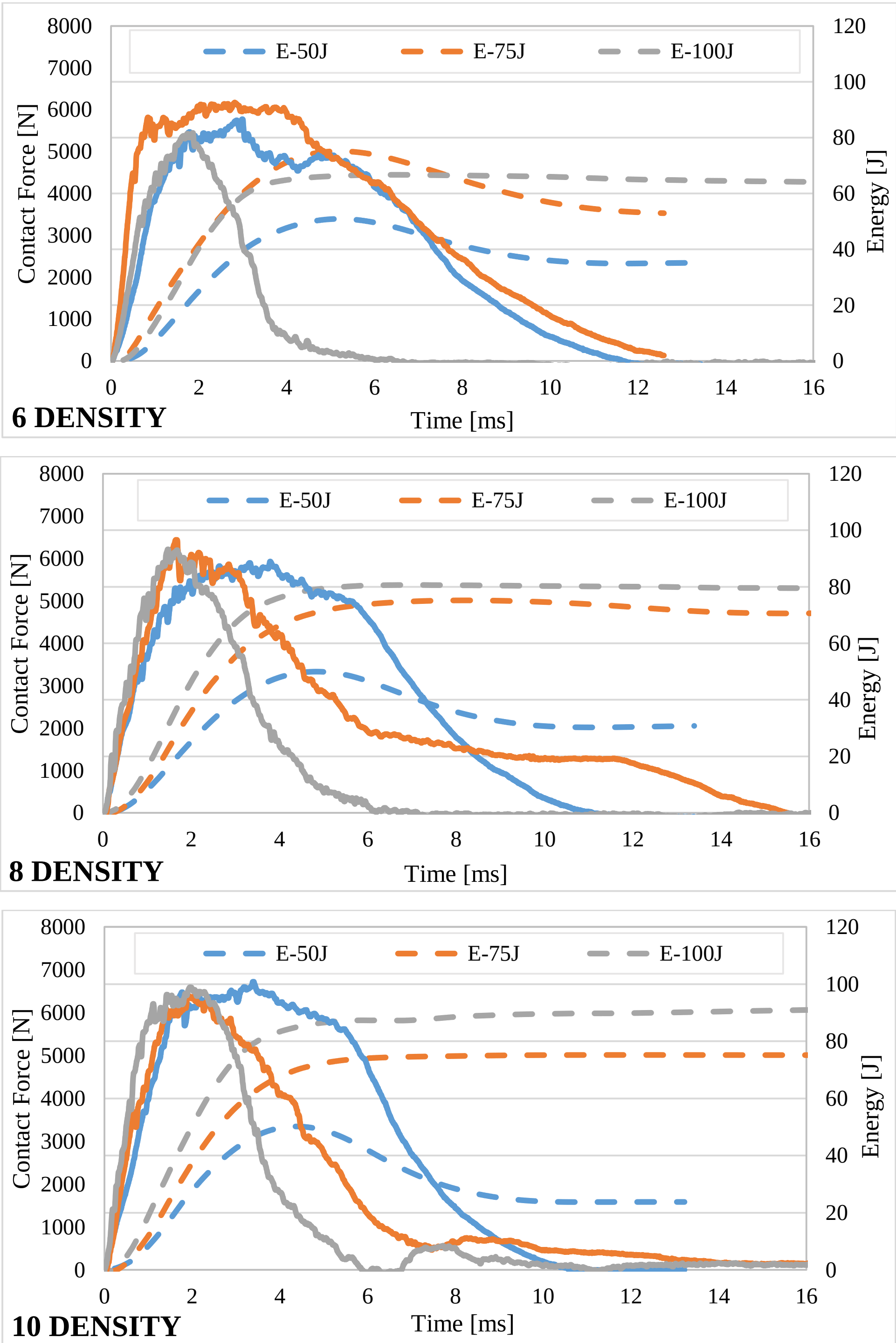


Figure 3.15 Contact force/energy-time graphics according to the impact energy for different densities

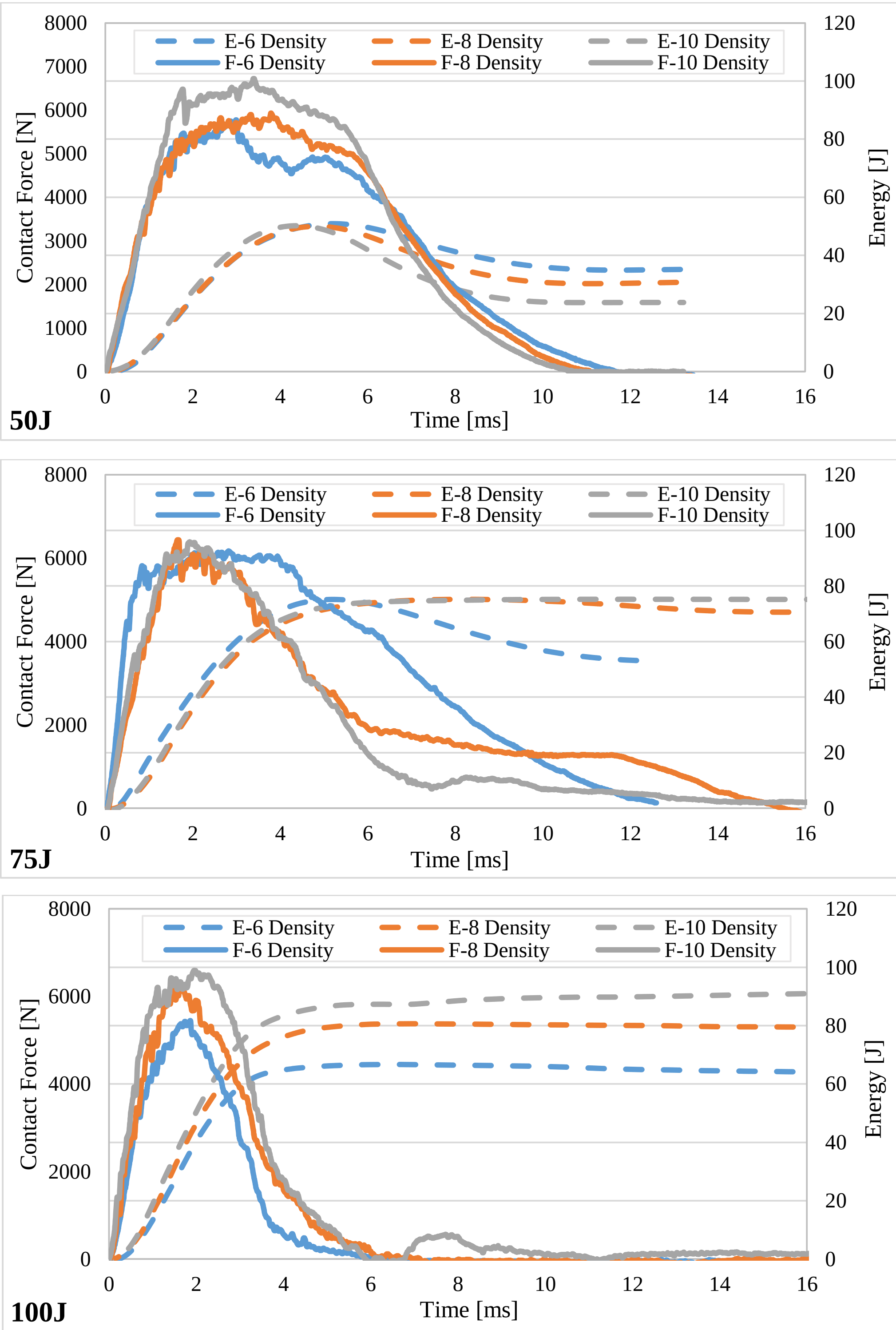
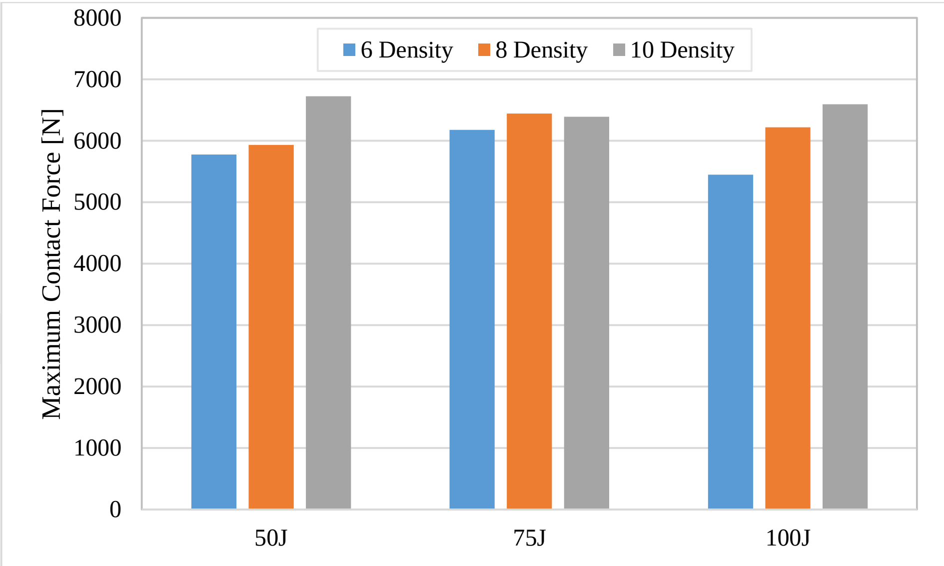
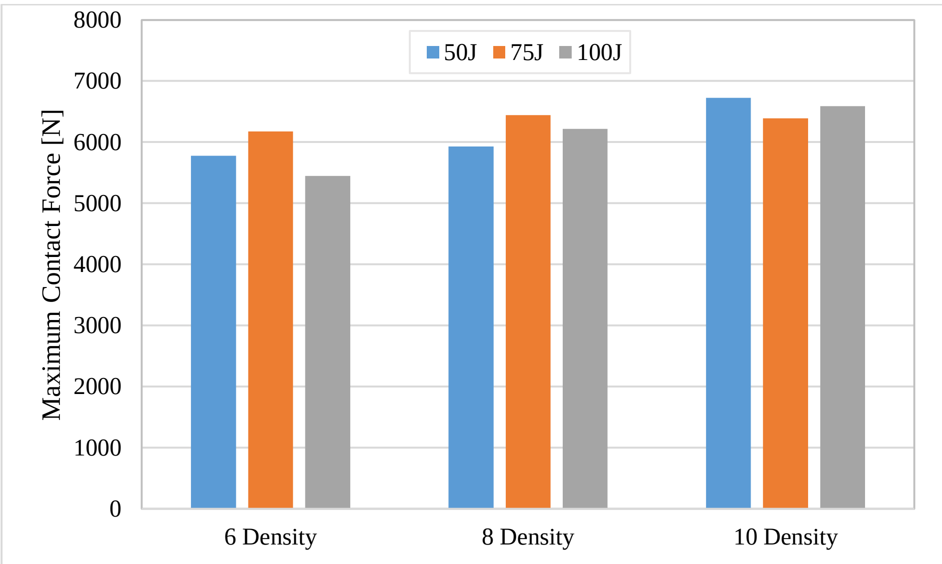


Figure 3.16 Contact force/energy-time graphics according to the density for different impact energies

The maximum contact force diagrams are separately shown for different energies and different densities in Figure 3.17. The maximum contact force was increased from 6 to 10-density in either 50 J or 100 J. However, 8-density had almost same maximum contact force with 10-density for 75 J energy level. As the 75 J was limit energy level for perforation, this phenomenon was occurred.



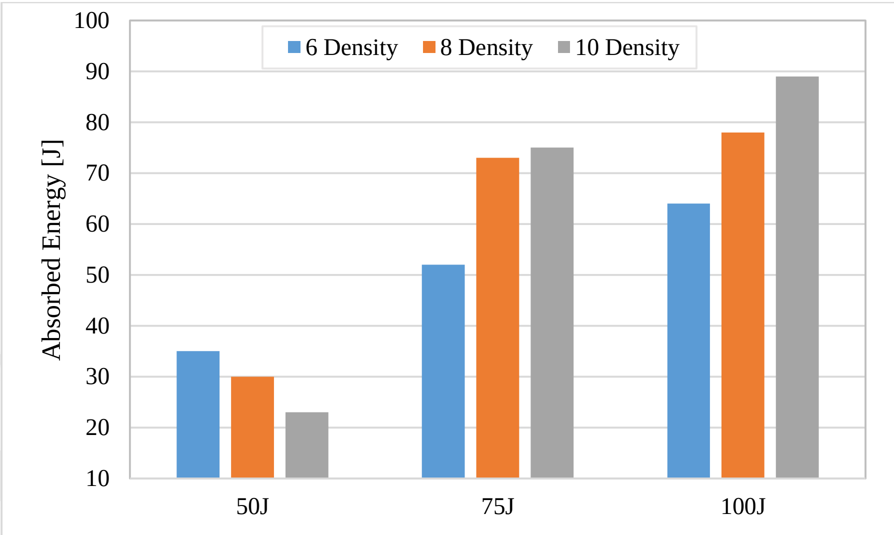
a)



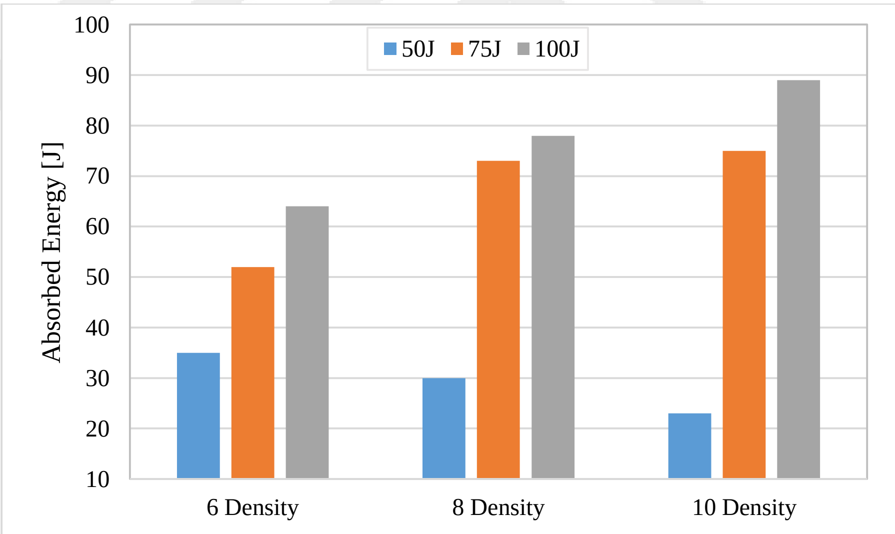
b)

Figure 3.17 Maximum contact force diagrams according to a) the densities for different impact energies, b) the impact energies for different densities

The absorbed energy diagrams for different energy levels are presented in Figure 3.18. It can be seen in the graph that the absorbed energy is linearly increased with the energy level for ever density value.



a)



b)

Figure 3.18 Absorbed energy diagrams according to a) the densities for different impact energies, b) the impact energies for different densities

3.3 Discussion

The structural properties of reinforcement characterize the mechanical properties of fibrous composites. Although natural fibers have outstanding properties in comparison with the synthetic fibers, its properties are strongly depended on the various conditions. The climate, soil fertility or quality of textile production processes can change the mechanical properties of fibers.

In this work, the flax yarns were used to produce woven fabrics and they were differentiated according to the weft densities. The woven fabrics have more uniform properties than fiber forms as reinforcement for composites Baghaei et al. (2015). The effects of number of weft densities were observed for mechanical and low impact properties of flax woven reinforced composites.

The tensile tests results shown that the 6-density composite demonstrated the highest tensile strength and modulus of elasticity values in warp direction. As the crimp percentage of warp yarn is increased from 6 to 10-density, the tensile strength and modulus of elasticity values decreased because the yarns cannot transfer all tensile load to the fabric as Rayyaan et al. (2020) concluded in their study. Besides, the Poisson's ratio was affected by the crimp percentage of warp yarns. On the other side, the tensile strength and modulus of elasticity values were proportionally raised in weft direction with the increasing density as same phenomena was obtained by Muralidhar (2013).

The samples showed similar compressive strength in the warp directions. Even if samples have trivial compressive strength differentiations in warp directions, these variations come from the nature of flax reinforced. The plant fiber reinforcement composites can behave non-linear in the mechanical tests as Muralidhar et al. (2020) already concluded. Nevertheless, the 6 and 8 weft density composites have not distinguishable differentiation in the weft direction in the compressive tests as like warp directions. However, the 10 weft density composite showed higher compressive stress value than other types of composites. It was detected, the number of yarn density increase the compressive strength of composite in the weft direction, but this effect is not strong when it compares with the tensile strength. In addition, the statistically meaningful differences could not be determined among the shear strength results.

Three types of measuring methods were used to obtain strain values of composites. While the raw data of tensile machine was affected from the unstable apparatus, the lights lead error the measuring of extensometer. Therefore, the strain-gage results were accepted as correct.

The composites were shown distinct contact force and energy absorption behaviors in 75J energy level. The 6, 8 and 10-density composites showed rebounding in this energy level, but 8 and 10 density composites were close to perforation. While the crack length is proportionally raised with the level of impact energy as Scarponi et al. (2016) found, it was reduced from 6 to 10 density. All composites were perforated in 100J and perforation shapes similar with flax composite samples of Papa et al. (2018). The contact force-displacement graphs showed that if the impact energy level is increased, the displacement value is raised. Moreover, it was detected that increasing of the weft density of flax woven reinforcement composites raised to the contact force value of samples like a study of Mishra et al. (2020). Besides, while displacement value of 6 density more than 10 density in 50J, the all densities' displacements were equal in the perforation energy level, which is 100J. The energy absorption capacities of samples were raised with the increased weft densities. However, the energy absorption capacity of material has inverse relationship with the weft density for low energy level.

CHAPTER FOUR

CONCLUSION

In this study, woven fabrics were produced from flax yarns and they were differentiated according to their weft densities. Then, flax woven fabric reinforced composites were manufactured by using the fabrics and epoxy matrix. The mechanical and impact properties of flax woven fabric reinforced composites were profoundly investigated.

According to the tests results, while the weft yarn density profoundly improves the tensile strength, tensile modulus and compressive strength of composites in the weft direction, the shear strength of composites were not affected. Additionally, the crimp percentage of warp yarns deeply impressed the tensile strength and tensile modulus of composite in the warp direction. However, the compressive strength of composites in warp direction was not significantly changed.

In the study the three different strain detect methods were used. The strain-gage gives the more accurate strain values than extensometer and tensile test machine because they were affected from the environmental factors such as light or unstable apparatuses.

The cracks were formed at 50 J impact energy level on the composites and the rebounding were observed. Moreover, the 6,8 and 10 density samples were shown rebounding in the 75J, but the 8 and 10 density samples were close to perforation. The samples were completely perforated at 100 J energy level. Impact tests results demonstrated that the contact force and energy absorption capacities of flax reinforced composites were profoundly affected by the weft density of reinforcement. Furthermore, the composites have distinct bending stiffness values in 100 J even though the stiffness of composites have similar values in 50 J energy level.

It is concluded that the weft density of reinforcement deeply affects the tensile and impact properties of flax woven reinforced composites. In addition, if the weft density is increased in the reinforcement, the flax woven reinforced composites mechanically behave more rigid and uniform.

The developing the computational model of flax reinforced composites, improving its mechanical properties thanks to the hybridization or applying the different types of mechanical tests can be considered as further studies.

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