INNOVATIVE TECHNOLOGY APPLICATIONS IN ENGINEERING SCIENCES



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Prof. Dr. Rakesh JAIN

Prof. Dr. Abdulkadir GÜLLÜ

Assist.Prof. Senai YALÇINKAYA

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Page Layout
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Kayaşehir Neighborhood Evliya Çelebi Street Emlakkonut Başakşehir Houses 1/A D Block Floor 4 Number 29 Başakşehir İstanbul - Turkey Phone: +902128014061- 62 Fax: +902128014063 Mobile: +9053331447861

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CONTENTS

PREFACE **4**

ÖNSÖZ **6**

PLANT-BASED FIBER-REINFORCED GEOPOLYMER COMPOSITES **8**
Kübra Ekiz BARIŞ

INDUSTRIAL VIEW TO FRICTION DRILLING TECHNOLOGY **46**
Mustafa ER, Bahattin YILMAZ, Abdulkadir GÜLLÜ

AN EVALUATION ON THE PRINCIPLES OF TRIBOLOGY AND USAGE IN WEAR APPLICATIONS **74**
Ezgi DOĞAN, Senai YALÇINKAYA, Memduh KURTULMUŞ

REACHING THE HIGHEST INFORMATION TRANSFER RATE VALUE IN EMOTIV EPOC-BASED BRAIN-COMPUTER INTERFACE SYSTEMS **96**
Mesut MELEK, Negin MELEK, Temel KAYİKCİOGLU

INVESTIGATION OF THE EFFECTS OF COATED AND UNCOATED DRILLS ON HOLE QUALITY IN DRILLING OF STEEL USED IN MOLDING **115**
Senai YALÇINKAYA, Alper ÖNER, Buğra BAŞIHOŞ

THE REVIEW OF LASER CLADDING METHOD AND PARAMETERS **140**
İbrahim KARAAĞAÇ, Mehmet Okan KABAKÇI, Mehmet Yasin DEMİREL

EVALUATION OF FLAME RETARDANTS FOR VARIOUS ENGINEERING MATERIALS **168**
Zafer KAHRAMAN

ENERGETIC INVESTIGATION OF A REFRIGERATOR WORK WITH DIFFUSION ABSORPTION REFRIGERATION CYCLE **198**
Mustafa ELEGELMEZ, Anıl BASARAN

AN OVERVIEW OF PALM FIBER REINFORCED COMPOSITES **224**
Yalçın BOZTOPRAK, Belma GJERGJJZI

THE IMPORTANCE OF HYDRAULIC SYSTEMS IN THE MACHINERY MANUFACTURING INDUSTRY **249**
Hayriye Sevil ERGÜR

PREFACE

In our world, while there are many negativities in the areas of nature, health, social, etc.; technological developments are becoming a necessity in the industry in general for the solution of these and other problems. Technological developments, triggered by quality competition, desire for comfort, fear and anxiety, emerge as a fact that we face in many and difficult to follow. Academic studies conducted in this context; It is brought together with its interlocutors, sometimes in the form of open-access sites, and sometimes in the form of congresses, panels, periodicals and scientific books.

We wanted to have a finger in the pie with this academic book study called **"Innovative Technology Applications in Engineering Sciences"** which consists of ten different chapters and covers the researches of valuable academicians. This book; we pre-sent it to you, valuable scientists and industry employees through "Güven Plus Grup Inc. Publications" which a major part of its publications consisting of academic books, has gained a great reputation with its qualified activities in the national and international arena.

This book consists of many engineering subjects and experimental studies and applied academic subjects. In the book;

You will find valuable research and experimental studies on many important subjects.

We believe that the book, which includes chapters dealing with many inter-esting topics of engineering technologies, will shed light on the academic studies of many researchers, and will find a valuable place in the catalogs of the Higher Education Institution, public libraries and personal archives.

We would like to express our gratitude to our esteemed editors, writers, ref-erees and you, our dear readers, who have contributed to the realization of this important work, which emerged as a result of the long-lasting and meticulous work. **December 2022**

Prof. Dr. Rakesh JAIN
Prof. Dr. Abdulkadir GÜLLÜ
Assist. Prof. Senai YALÇINKAYA

ÖNSÖZ

Dünyamızda doğa, sağlık, sosyal vb. alanlarda birçok olumsuzluk yaşanırken; bunların ve diğer problemlerin çözümüne yönelik olarak genel anlamda endüstride, teknolojik gelişmeler zorunluluk halini almaktadır. Kalite rekabeti, konfor arzusu, korku ve endişenin de tetiklediği teknolojik gelişmeler, takipte zorlanılacak derecede ve çok sayıda yüzleştiğimiz bir gerçek olarak karşımıza çıkmaktadır. Bu bağlamda yapılan akademik çalışmalar; kimi zaman açık erişimli siteler, kimi zaman da kongre, panel, süreli yayınlar ve bilimsel kitaplar şeklinde muhataplarıyla buluşturulmaktadır.

Biz de birbirinden kıymetli akademisyenlerin araştırmalarını kapsayan, on farklı bölümden oluşan **""Innovative Technology Applications in Engineering Sciences"** adını verdiğimiz bu akademik kitap çalışması ile çorbada tuzumuz olsun istedik. Bu kitabı; yayınlarının önemli bir bölümünü akademik kitaplardan oluşan, Ulusal ve Uluslararası alanda nitelikli faaliyetleriyle oldukça saygınlık kazanmış olan "Güven Plus Grup A.Ş. Yayınları" aracılığı ile siz değerli bilim insanları ve endüstri çalışanlarının hizmetine sunuyoruz.

Bu kitap, birçok mühendislik konuları ve deneysel çalışmalar ile uygulama yapılmış akademik konulardan meydana gelmiştir. Kitapta;

Birçok problemlerin çözümüne yönelik birçok önemli konuda değerli araştırma ve deneysel çalışmaları bulacaksınız.

Mühendislik teknolojilerinin birçok ilgi çekici konularına değinilen bölümlerin yer aldığı kitabın, çok sayıda araştırmacının akademik çalışmalarına ışık tutacağına, Yükseköğretim Kurumu kataloglarında, kamu kütüphanelerinde ve kişisel arşivlerde oldukça değerli bir yer bulacağına inanıyoruz.

Uzun zaman alan ve büyük bir titizlikle yapılan çalışmaların sonucu olarak ortaya çıkan bu önemli eserin gerçekleşmesinde emeği geçen saygıdeğer editörlerimize, yazarlarımıza, hakemlerimize ve kitabımızı edinen siz sevgili okurlarımıza teşekkürlerimizi sunarız. **Aralık 2022**

Prof. Dr. Rakesh JAIN
Prof. Dr. Abdulkadir GÜLLÜ
Dr. Öğr. Üyesi Senai YALÇINKAYA

PLANT-BASED FIBER-REINFORCED GEOPOLYMER COMPOSITES

Kübra Ekiz BARIŞ[1]

Abstract: The excessive production of Portland cement is becoming unsustainable because of an enormous requirement for raw materials, energy use, greenhouse gas emissions, and environmental damage. Because of the aforementioned negative effects, it is essential to develop and utilize alternative binders that have lower carbon footprints. Recent research on geopolymer binders indicates that this novel binder has the potential to replace cement. There is a reduced effect on the environment from these binders because they use less calcium-based raw materials. They are also more energy-efficient because there is no calcination during the production stages and the production temperature is lower. However, the usage of geopolymers in various applications may be adversely impacted by their low tensile strength, brittle nature, and limited crack resistance. The geopolymer matrix can be reinforced with either short or continuous fibers to enhance the mechanical properties of the material, decrease brittle fracture, and enhance ductility. Natural fibers are now preferred over other fibers in the reinforcing of geopolymers due to the recent trend toward the production of environmentally friendly and energy-efficient materials. In contrast to the quantity of studies concentrating on inorganic and synthetic fiber reinforcement, it is, nevertheless, comparatively insufficient. The goal of the current chapter is to compile the most recent scientific data on the impact of plant-based fiber reinforcement on the enhancement of the mechanical and physical characteristics of geopolymer composites. The Scopus and SCI databases were checked for recently published articles on plant-based fiber-reinforced geo-

1 Kocaeli University, Faculty of Architecture and Design, Kocaeli / Turkey, e-mail: kubra.ekizbaris@kocaeli.edu.tr, Orcid No: 0000-0002-3830-7185

polymer composites. The characteristics (chemical structure, physical, and mechanical properties) of plant-based fibers, mixture ratios, production stages, and curing conditions of plant-based fiber-reinforced geopolymer composites are also within the scope. Various plant-based fibers, including sisal, coir, jute, cotton, hemp, lignin, raffia, pineapple, bamboo, musa basjoo, sorghum, and sugarcane bagasse, can be incorporated as reinforcement in geopolymer matrices, according to study results. In order to produce plant-based fiber-reinforced geopolymer composites with higher physical and mechanical characteristics, it is vital to consider the type, chemical structure, and characteristics of the fibers as well as their content, manufacturing process, and curing conditions. The uniform dispersion of the fibers and matrix must be maintained throughout production since balling and fiber coalescence weaken the necessary properties. Depending on the characteristics of the fiber and the aluminosilicate source, the appropriate curing conditions should be applied. The workability of fiber-reinforced geopolymers was worse than that of the unreinforced geopolymer matrix, regardless of the type of fiber utilized. More water is added to the matrix to decrease the viscosity of the geopolymer. During temperature curing, this free water evaporates, leaving a significant number of pores in the microstructure. As a result, adding fibers causes composites' porosity and water absorption ratio to increase while their density and ultrasound pulse velocity decrease. Flexural, compressive, and impact strengths of unreinforced geopolymers increase with increasing fiber content until they reach their optimum amount. However, inclusion of additional fibers over the optimum level results in the fibers balling and coalescing, and also leaves voids in the matrix, which weakens the interfacial adhesion between the fiber and the matrix and, in turn, lowers the mechanical properties.
Keywords: Geopolymer Composite, Plant-Based Fiber, Fiber Content, Strength

INTRODUCTION

Climate change, one of the most important environmental problems facing our planet, is caused by CO_2 emissions. The atmospheric CO_2 ratio in the 18th century was 280 ppm per million, while today it is 450 ppm. If progress continues at this rate, it is predicted that the CO_2 ratio will be 731 ppm in 2130 (Pacheco-Torgal, 2015). The very large-scale production of Portland cement is becoming unsustainable due to an unprecedented

need for raw materials, energy consumption, greenhouse gas emissions, and environmental pollution (Farhan et al., 2021). Cement production is responsible for 5% of global CO_2 emissions, which is quite a high rate (IPCC, 2001). Significant consumption of traditional non-renewable raw materials such as limestone, calcination of clinker at 1400 1450 °C, energy consumption for the grinding process, and high greenhouse gas emissions (0.9 tons of CO_2 emissions per 1 ton of clinker production) are adverse effects of cement-based materials (Hendriks et al., 1999). Therefore, the aforementioned adverse effects make it necessary to develop and use alternative binders with lower carbon footprints (Ganesan et al., 2013).

Recent studies on geopolymer binders show that this new binder can be an alternative to Portland cement. Geopolymer binders are obtained as a result of the reaction of an amorphous or glassy aluminosilicate source with various alkali activators (Garcia-Lodeiro et al., 2015). Various natural materials, including agricultural, industrial, and urban waste materials, containing mostly silica (SiO_2) and alumina (Al_2O_3), can be used as an aluminosilicate source. Alkali hydroxides, weak and strong acid salts, and silica salts are various chemical solutions used as alkali activators (Robayo-Salazar and de Gutiérrez, 2018). Because less calcium-based raw materials are used in these binders, the environmental impact is lower. In addition, they are more energy-efficient due to the absence of a calcination stage in the production process, the lower production temperature, and the need for less fuel (Bondar et al., 2011). CO_2 emissions from geopolymer production are approximately 60-80% lower than those from conventional cement production (Zhang et al., 2014).

The reaction mechanism of geopolymers is an exothermic process and consists of successive dissolution, oligomerization, and polycondensation reactions. The first reaction begins with the dissolution of covalently bonded Si–O–Si and Al–O–Si compounds from the aluminosilicate source by means of an alkali solution, and silicate and aluminate monomers are formed. These silicate and aluminate monomers form an oligomer during the oligomerization stage. Then, the oligomers condense and cross-linking occurs between various polymeric chains to

form a three-dimensional geopolymer network (NASH gel) (Ferone et al., 2011).

Geopolymer binders have the following advantages, depending on the properties of the aluminosilicate source, the alkali activator type, the mixing ratio, and the production and curing conditions (Davidovits, 2011; Provis and Bernal, 2014; RILEM TC 224-AAM, 2014):

- *High compressive strength (compressive strength that can increase up to 90 MPa for 28 days)*
- *Rapid hardening, reaching 70% of its ultimate compressive strength within 4 hours (Comrie et al., 1989). This value is approximately 24 hours for Portland cement.*
- *Thermal stability up to 1200 °C (Zheng et al., 2009; Abdul Aleem and Arumairaj, 2012)*
- *Exhibiting excellent adhesion with other materials,*
- *Reduced permeability and dimensional stability (low shrinkage),*
- *Durability against acid and chemical effects.*

Despite the advantages mentioned above, geopolymers' low tensile strength, brittle behavior, and low resistance to cracks can negatively affect their use in many applications. There are two approaches applied in order to improve the mechanical properties of the material (such as its tensile, flexural, and impact strengths), and to suppress brittle behavior and to provide ductility. In the first approach, the geopolymer matrix is reinforced with nanoparticles, and in the second approach, the matrix is reinforced with either short or continuous fibers. Considering factors such as practicality and production cost during production, reinforcement of the geopolymer matrix with short fibers is more preferred in civil engineering applications (Abbas et al., 2022).

In the literature, there are studies on the reinforcement of geopolymers with steel, inorganic, synthetic, and natural fibers. However, recently, the trend towards producing ecologically friendly and energy-saving materials has brought about the preference of natural fibers over other fibers in the reinforcement of geopolymers (Silva et al., 2020). However, it is relatively insufficient in comparison to the number of the works focuses on the reinforcement with inorganic and synthetic fibers.

Natural fibers are classified into three groups: mineral-based, animal-based, and plant-based fibers. The use of mineral-based fibers in geopolymers leads to high environmental impact because their production requires melting and spinning the mineral at high temperatures, and several processing steps are required before usage (Alzeer and MacKenzie, 2021). In addition, some mineral-based fibers, such as asbestos, are carcinogenic materials. On the other hand, animal-based fibers are not convenient for producing a large-scale geopolymers due to the difficulty in collecting them from animals (Silva et al., 2020). Since plant-based fibers are more cost-effective and easier to apply, they are the most suitable natural fiber type in terms of being used in the production of geopolymer materials.

The aim of the current chapter is to synthesize the latest research findings regarding the influence of plant-based fiber reinforcement on the improvement of the physical and mechanical properties of geopolymer composites. Recently published articles on plant-based fiber-reinforced geopolymer composites in the Scopus and SCI databases are reviewed. Only the effectiveness of "randomly oriented short fibers" on the properties is included in the study because they don't need specialized production methods and conventional production techniques can be used (Silva et al., 2020). The effectiveness of continuous fibers (fabrics) is excluded. The characteristics of plant-based fibers, mixture ratios, production process, and curing conditions of plant-based fiber-reinforced geopolymer composites are also within the scope of the current section.

THE COMPONENTS of PLANT-BASED FIBER-REINFORCED GEOPOLYMER COMPOSITES

A geopolymer composite reinforced with plant-based fiber consists of three basic components: (i) an aluminosilicate source, (ii) an alkali activator, and (iii) plant-based fiber (Figure 1). The aluminosilicate sources are various natural or artificial raw materials having high silica and alumina contents. The widely used alkali activators are sodium silicate (SS), sodium hydroxide (NaOH), and potassium hydroxide (KOH), and their combinations in various proportions (NaOH +SS and KOH+SS), which react with the aluminosilicate source to form geopolymer binders. In the

literature, geopolymer binders and mortars are reinforced with different types of plant-based fibers, such as sisal, jute, coir, cotton, hemp, lignin, raffia, pineapple, bamboo, musa basjoo, sorghum, and sugarcane bagasse, as shown in Figure 1.

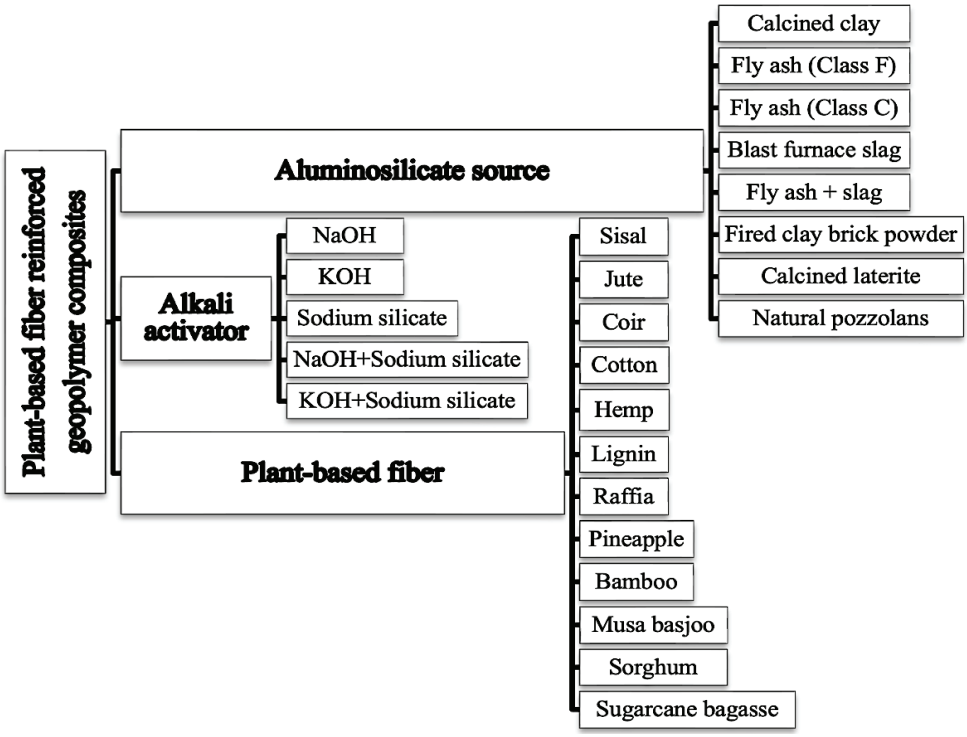


Figure 1. The Components of Plant-Based Fiber-Reinforced Geopolymer Composites

Chemical Structure of Plant-Based Fibers

Wood and non-wood fibers are the two subcategories of plant-based fibers. These latter materials are known as lignocellulose fibers, and they can be further separated into stem or bast fibers (such as hemp, jute, and flax), seed fibers (such as cotton), leaf fibers (such as banana, pineapple, and sisal), coir fibers (such as coconut), grass fibers (such as bamboo), and straw fibers (such as rice) (Alzeer and MacKenzie, 2021).

Cellulose, hemicellulose, and lignin are the main components of all plant-based fibers. Their chemical composition differs according to the

type of plant, location, climate, technique of harvesting, and plant maturity (Santana et al., 2021). Table 1 presents the chemical compositions of plant-based fibers frequently preferred as reinforcements in geopolymer matrices. Cellulose is a hydrophilic glucan polymer made from a straight chain of glucose compounds connected by β(1→4) bonding. The mechanical strength of the plant-based fibers is influenced by the orientation of the cellulose microfibrils (Alzeer and MacKenzie, 2021) and by the degree of cellulose polymerization, which varies according to the type of plant (Silva et al., 2020). Therefore, plant-based fibers with a high cellulose content (such as cotton, hemp, flax, and pineapple) are the most preferred ones to be used as a reinforcement in geopolymer matrices.

Table 1. Chemical Compositions of Plant-Based Fibers

		Chemical composition (wt %)			
Reference	Fiber type	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Others (%)
(Pacheco-Torgal and Jalali, 2011)	Coir	31	19.2	29.7	20.1
(Jawaid and Abdul Khalil, 2011)	Flax	64.1	16.7	12	7.2
(Silva et al., 2020)	Jute	58–63	58–63	12– 15	-
	Sisal	43–56	21–24	7–9	-
(Mishra et al., 2004)	Pineapple	70-82	-	5-12	6-25
(Gassan and Bledzki, 1996)	Cotton	82.7	5.7	-	11.6
(Yan et al., 2016)	Bamboo	34.5	20.5	26	19
	Abaca	62.5	21	12	4.5
(Poletanovic et al., 2020)	Hemp	74.4	17.9	3.7	1.7
(Pacheco-Torgal and Jalali, 2011)	Banana	31.5	15.0	15.0	38.5

Hemicellulose is an amorphous, cross-linked polymer consisting of complex saccharide monomers (Alzeer and MacKenzie, 2021). Hemicel-

luloses connect and stabilize the cellulosic micro-fibers to increase the stability of the fibers rather than acting as load-bearing components. In contrast to the crystalline structure of cellulose, the structure of hemicellulose is entirely amorphous, which makes it more susceptible to an alkaline environment (Santana et al., 2021).

Lignin is an amorphous, complex aromatic hydrocarbon polymer and gives plants their structural support (Alzeer and MacKenzie, 2021). Lignin works as an adhesive, keeping the cellulosic units connected to one another. However, as with hemicellulose, the amorphous structure of lignin makes it vulnerable to deterioration (Santana et al., 2021). Pectin, a heteropolysaccharide that gives plants flexibility, is frequently present in the fibers of bast and fruits (Alzeer and MacKenzie, 2021).

Physical and Mechanical Properties of Plant-Based Fibers

Plant fibers provide a number of desirable benefits over synthetic fibers, including low cost, low weight, wide availability, biodegradability, recyclable resources, the desired aspect ratio, and strong tensile strength (Silva et al., 2020). The density of plant-based fibers varies between 1.2 and 1.5 g/cm^3, their tensile strength is between 120 and 900 MPa, their modulus of elasticity is between 4.8 and 90 GPa, and their ultimate elongation is between 0.59 and 25%, depending on the fiber type, length, chemical structure, and maturity level. They absorb moisture and water easily, and they are weakly dimensionally stable. When these fibers are incorporated in mortars, the hydrophobic and hydrophilic properties of the fibers and their interactions with the matrix can have an impact on how well they adhere to the matrix. The lower mechanical properties of the material can be caused by the existence of pendant hydroxyl and polar groups, which can result in significant moisture absorption and poor fiber-matrix adhesion (Yan et al., 2016).

According to the literature (Biagiotti et al., 2004), there are nearly 2.5 billion hydrogen bonds in cellulosic fibers. Even though hydrogen bonds only have about 1/10 the strength of covalent bonds, the high tensile strength of these fibers is due to the predominance of 2.5 billion hydrogen bonds. So, compared with synthetic fibers, plant-based fibers exhibit similar specific mechanical properties (Santana et al., 2021). The

tensile strength of cellulose fibers declines as fiber length increases because long fibers may have more imperfections and break rapidly compared to short fibers (Silva et al., 2020).

Plant-Based Fiber Content in Geopolymer Composites

Fiber content is often represented as a weight percentage (wt%) or volume fraction (vol%), as shown by Table 2. Some researchers selected to describe the inclusion of fiber in terms of the weight/volume of the aluminosilicate source (0.2-10%), whereas other researchers selected to describe the addition of fiber in terms of the weight/volume of the total of the raw materials (1-5%). A fiber with a smaller shape generates more fibers compared to a fiber with a larger shape for the same volume fraction.

MANUFACTURING PROCESS, CURING CONDITIONS and APPLIED TESTS of PLANT-BASED FIBER-REINFORCED GEOPOLYMER COMPOSITES

Throughout time, many methods, including extrusion, 3D printing, cold and hot pressing, have been used to mix and place geopolymer composites. However, the order in which the fibers are added must be carefully considered because it has a significant impact on the dispersion of the fibers and the uniformity of the matrix. Fiber surface deposition, fiber balling, and agglomeration should be avoided (Farhan et al., 2021) during mixture process.

Generally, the randomly oriented short fibers are blended with the aluminosilicate source in dry conditions for a short period of time. Afterwards, an alkali activator is gradually added, and the mixture process is continued until homogeneity is achieved (Alomayri et al., 2013). However, in some investigations, the fibers are finally incorporated into the geopolymer matrix after the mortar completely prepared (Ribeiro et al., 2016). The mixing period is extended for longer fibers with a high aspect ratio until uniform distribution is attained.

The curing conditions (curing temperature, duration, and humidity) have such an influence on how the geopolymer structure develops

as well as the final product's properties that it is essential to select the most effective curing conditions. The performance of the produced material may be deteriorated by improper curing, which can increase porosity and permeability and decrease mechanical properties. The curing temperature is the most important factor. Although heat curing takes more energy, it is frequently applied because the aluminosilicate precursor needs energy to start the geopolymerization reactions (Athira et al., 2021). Because the beginning of setting is delayed and the rate of the chemical reaction is incredibly slow, geopolymers cannot be successfully cured at temperatures below room temperature (7–20 °C) (Jiang et al., 2022; Nath and Sarker, 2015; Wang et al., 2004; Hardjito et al., 2004; Heah et al., 2011). The increase in curing temperature to 90 °C enhances the dissolution of an aluminosilicate source (Heah et al., 2011), increases cross-linking in an amorphous structure (Ferone et al., 2011), and finally increases the compressive strength of the material (Wang et al., 2004; Chindaprasirt et al., 2007).

Curing conditions for plant-based fiber-reinforced geopolymer composites are presented in Table 2. Depending on the type of aluminosilicate source, a variety of thermal curing conditions are used, ranging from ambient temperature to 90°C for 1 to 24 hours. Some studies have increased the curing temperature and period to over 90°C (Alomayri and Low, 2013) and 24 hours (Silva et al., 2020; Wongsa et al., 2020).

According to the Table 2, the physical properties of plant-based fiber-reinforced geopolymer composites are investigated in terms of workability, density, porosity, water absorption ratio, thermal conductivity, and ultrasound pulse velocity (UPV), while the mechanical properties are investigated in terms of flexural strength, compressive strength, impact strength, and hardness. In addition, the effects of fiber addition on the toughness of the unreinforced geopolymers are also determined in the experimental studies.

Table 2. Aluminosilicate, Activator and Fiber Types, Fiber Contents, Curing Conditions, and Applied Tests of Plant-Based Fiber-Reinforced Geopolymer Composites

Ref	Aluminosilicate precursor	Activator type	Fiber type	Fiber length (mm)	Fiber Content (wt% of precursor)	Curing	Workability	Density	Porosity	Water abs.	Thermal cond.	UPV	Flexural strength	Compressive Strength	Impact strength	Hardnes
(Wongsa et al., 2020)	High calcium fly ash	10 M NaOH+ SS*	Sisal	35–40	0	60 ° C for 48 h	•	•	•	•	•	•	•	•		
					0.5**		•	•	•	•	•	•	•	•		
					0.75**		•	•	•	•	•	•	•	•		
					1**		•	•	•	•	•	•	•	•		
			Coir	35–40	0		•	•	•	•	•	•	•	•		
					0.5**		•	•	•	•	•	•	•	•		
					0.75**		•	•	•	•	•	•	•	•		
					1**		•	•	•	•	•	•	•	•		
(Su et al., 2019)	Fly ash (70%) + slag (30%)	10 M NaOH+ SS	Lig-nin	-	0*	60 ° C for 24 h	•						•	•		
					0.25*		•						•	•		
					0.5*		•						•	•		
					0.75*		•						•	•		
					1*		•						•	•		
					1.25*		•						•	•		
(Silva et al., 2020)	Fired clay brick powder	8 M NaOH+ SS	Sisal	10	0	65 ° C for 72 h	•	•					•	•		
					0.5		•	•					•	•		
					1		•	•					•	•		
					1.5		•	•					•	•		
					2		•	•					•	•		
					2.5		•	•					•	•		
					3		•	•					•	•		
			Jute	10	0		•	•					•	•		
					0.5		•	•					•	•		
					1		•	•					•	•		
					1.5		•	•					•	•		
					0		•	•					•	•		

(Reddy et al., 2022)	Fly ash	6, 8, 10, and 12 M NaOH	Musa basjoo	20	0	-	•			•			•	•		
					0.25		•			•			•	•		
					0.5		•			•			•	•		
					0.75		•			•			•	•		
					1		•			•			•	•		
					1.25		•			•			•	•		
					1.5		•			•			•	•		
(Alomayri and Low, 2013)	Fly ash	8 M NaOH+ SS	Cotton	10	0	105 C for 3 h		•	•				•	•	•	•
					0.3			•	•				•	•	•	•
					0.5			•	•				•	•	•	•
					0.7			•	•				•	•	•	•
					1.0			•	•				•	•	•	•
(Yanou et al., 2021)	Calcined laterite	10 M NaOH+ SS	Sugarcane bagasse	-	0	at room temperature for 28 days		•	•	•				•		
					1.5			•	•	•				•		
					3			•	•	•				•		
					4.5			•	•	•				•		
					6			•	•	•				•		
					7.5			•	•	•				•		
(Nkwaju et al., 2019)	Calcined laterite	10 M NaOH+ SS	sugarcane bagasse	20	0	at room temperature for 28 days					•		•			
					1.5						•		•			
					3						•		•			
					4.5						•		•			
					6						•		•			
					7.5						•		•			
(Poletanovic et al., 2020)	fly ash and fly ash/slag	SS	Hemp	10	0**	20C, 60C, and 80C for 24 h		•		•			•	•		
					0.5**			•		•			•	•		
					1**			•		•			•	•		

SS=Sodium Silicate
*= the addition of fiber in terms of the mass of total dry materials
**= the addition of fiber in terms of the volume of total dry materials

PHYSICAL PROPERTIES of PLANT-BASED FIBER-REINFORCED GEOPOLYMER COMPOSITES

Workability

The higher qualities during the fresh condition are crucial to obtain higher mechanical properties after hardening (Abbas et al., 2022). The influence of fiber content on the workability of geopolymer composites is given in Figure 2.

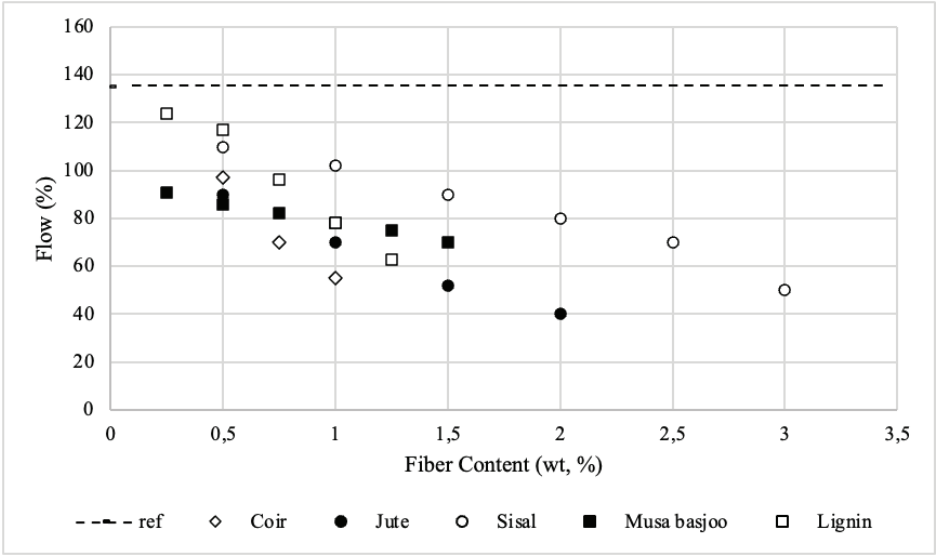


Figure 2. Influence of Plant-Based Fiber Content on the Workability of Geopolymer Composites, Adopted from Refs. (Silva et al., 2020; Wongsa et al., 2020; Su et al., 2019; Reddy et al., 2022)

The flow value of geopolymer matrices without fiber is in the range of about 130-135%. The workability of geopolymers containing various types of fibers was lower than that of the unreinforced geopolymer matrix, and this effect is independent of the type of fiber used. This is a result of the hydrophilic plant-based fiber's high moisture absorption. A significant shear force in between the matrix and fibers, which hinders fluidity and leads to a less workable matrix, is another factor contributing to this behavior (de Azevedo et al., 2021).

The content of fibers present in the geopolymer matrix affects the degree of workability reduction. With the inclusion of more fiber, the flow of all geopolymer mortars decrease. As seen in Figure 2, the flow fluctuates between 40 and 125% depending on the fiber ratio. Low fiber dispersion is observed at higher fiber contents (Su et al., 2019). The possibility of adding more water to compensate for this loss of workability should not be taken into account because it will reduce the mechanical properties of the material (Silva et al., 2020). Therefore, the fiber con-

tent should have a saturation limit in order to prevent challenges during molding and vibration of the fresh mixture (Silva et al., 2020). The maximum contents of coir, jute, sisal, musa basjoo, and lignin fibers are 1, 2, 3, 1.5, and 1.25, respectively. Since the casting process becomes incredibly difficult, a higher fiber content is not feasible.

The level of workability reduction in geopolymers is influenced by the aspect ratio of the fibers. As seen in Figure 2, for the same fiber content (for instance, 2 wt%), geopolymer composites reinforced with sisal fibers demonstrates a flow capacity that is 50% higher than that of jute fibers. This is explained by the lower aspect ratio that sisal fibers provide. As the aspect ratio increases, fiber-reinforced geopolymers become less workable (Silva et al., 2020).

Porosity and Density

Porosity is a key factor that greatly impacts the other mechanical and physical properties of geopolymer materials. The influence of fiber content on the porosity of geopolymer composites is given in Figure 3.

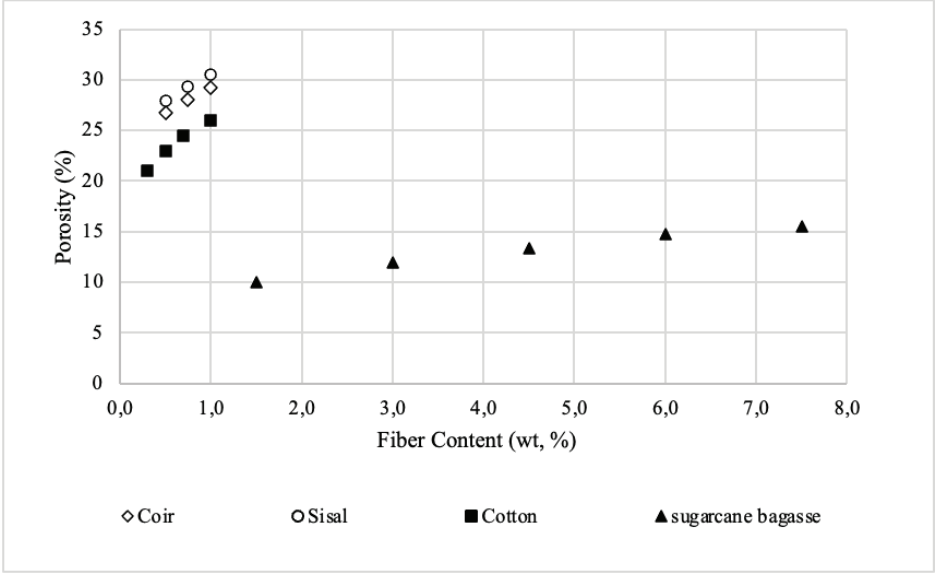


Figure 3. Influence of Plant-Based Fiber Content on the Porosity of Geopolymer Composites, Adopted from Refs. (Wongsa et al., 2020; Alomayri and Low, 2013; Yanou et al., 2021)

Generally, with the inclusion of plant-based fibers, the porosity of composites increases. While the porosity of the unreinforced geopolymer matrix is 27%, when the matrix is reinforced with 0.5, 0.75, and 1% sisal fiber, the porosity increases by 1.02, 1.10, and 1.15 times, respectively. When the same matrix is reinforced with the same proportion of coir fiber, the porosity increases 1.03, 1.05, and 1.09 times, respectively. The porosity of the geopolymer matrix is also increased by 1.05, 1.15, 1.22, and 1.30 times, respectively, by the incorporation of cotton fiber at concentrations of 0.3, 0.5, 0.7, and 1.0%. Higher contents of sugarcane bagasse fibers (1.5, 3.0, 4.5, 6.0, and 7.5%) increase the porosity of the matrix (10%), which is lower in the first case compared to other studies by 1.05, 1.09, 1.22, 1.34, and 1.40 times, respectively. The fact that fibers absorb water because of their porous structure may also help to explain why porosity increases as fiber concentration increases (Alomayri et al., 2013). A higher water ratio is necessary to lower the viscosity of fiber-reinforced geopolymers, and this leads to an increase in porosity. The higher amounts of water incorporation leads to more free water that is trapped inside inter-granular space and large pores after geopolymerization. During curing, this water evaporates, leaving a large number of inter-granular pores in the microstructure. In order to have a homogeneous microstructure, fiber clumping, which may be increased by a higher fiber content, is undesirable (Alomayri et al., 2013).

The influence of fiber content on the density of geopolymer is given in Figure 4.

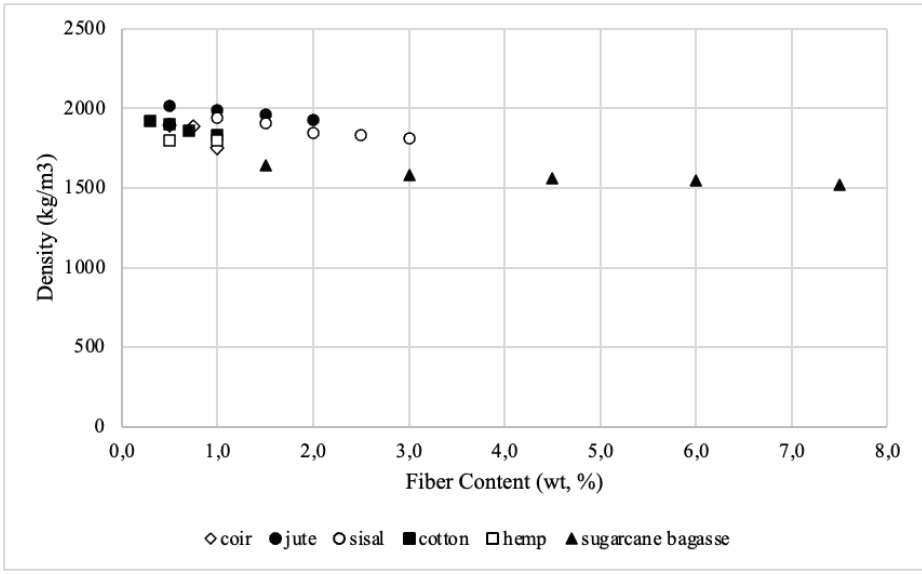


Figure 4. Influence of Plant-Based Fiber Content on the Density of Geopolymer Composites, Adopted from Refs. (Silva et al., 2020; Poletanovic et al., 2020; Wongsa et al., 2020; Alomayri and Low, 2013; Yanou et al., 2021)

Sisal fibers (up to 1% by weight) reduce the density of the reference geopolymer mortar by 0.97 times, while coir fibers decrease by 0.92 times. Incorporating cotton fibers (0.30, 0.50, 0.70, and 1.00 %) gradually decrease the density of the mortar by 0.96, 0.95, 0.93, and 0.91 times, respectively. Hemp fibers added at the content of 0.50% and 1.00% provide 0.96 and 0.95 times decrease in the density of the geopolymer composite, respectively. In addition, the density of sugarcane bagasse fiber-based geopolymer composites with higher contents (from 0% to 1.5%, 3%, 4.5, 6, and 7.5) decrease 0.98, 0.97, 0.96, 0.95, and 0.94 times, respectively. Generally, the decrease in density of fiber-reinforced mortars is the result of their higher porosity. In addition, regardless of the type of composite, density decreases as fiber content increases. Due to an increase in fiber content, the fibers clustered during mixing (Alomayri et al., 2013), and an uneven dispersion of fibers inside the matrix encourages the formation of fiber coalescence and voids confined between them. These spaces are filled with water when the matrix is in a fresh state, but as it

hardens, the evaporation of the water causes the composite to become porous and less dense (de Azevedo et al., 2021). Additionally, the final density of the composites is lower due to the reduced density of plant-based fibers themselves (Poletanovic et al., 2020). Contrary to other studies, the bulk density is maximized at a specific fiber content (1% for both sisal and jute fiber-reinforced geopolymers). The increase in density in comparison to the unreinforced matrix is explained by the greater compaction energy used throughout production because of workability loss and the increased viscosity due to fiber addition. However, when the fiber content is higher than 1%, the density decreases. Even though more compaction energy is used during production (at 1% fiber content), this loss in bulk density may be due to fiber agglomeration during mixing at high fiber content (Silva et al., 2020).

Water Absorption Ratio

Macropores and wider capillary pores, both of which are larger than 1 μm, are able to permit water to penetrate (Poletanovic et al., 2020). The influence of fiber content on the water absorption ratio of geopolymer composites is given in Figure 5. Plant-based fiber-reinforced geopolymer composites absorb more water as their porosity and density increase. While the water absorption ratio of the unreinforced geopolymer matrix is 5%, the water absorption values increase approximately 1.20, 1.22, and 1.26 times when the material is reinforced with 0.5, 0.75, and 1% sisal fiber, respectively. When the same matrix is reinforced with the same amount of coir fiber, the effect of fiber content on water absorption is not significant. The addition of 1.5, 3.0, 4.5, 6, and 7.5% sugarcane bagasse fibers leads to an increase in the water absorption ratio of the unreinforced matrix (18%) by approximately 1.06, 1.11, 1.17, 1.22, and 1.33 times, respectively. In comparison to the unreinforced specimen, the increasing level of the water absorption ratio of hemp fiber-reinforced geopolymers (with 0.5 and 1% fiber content) is the highest, approximately 1.48 and 1.57 times, respectively.

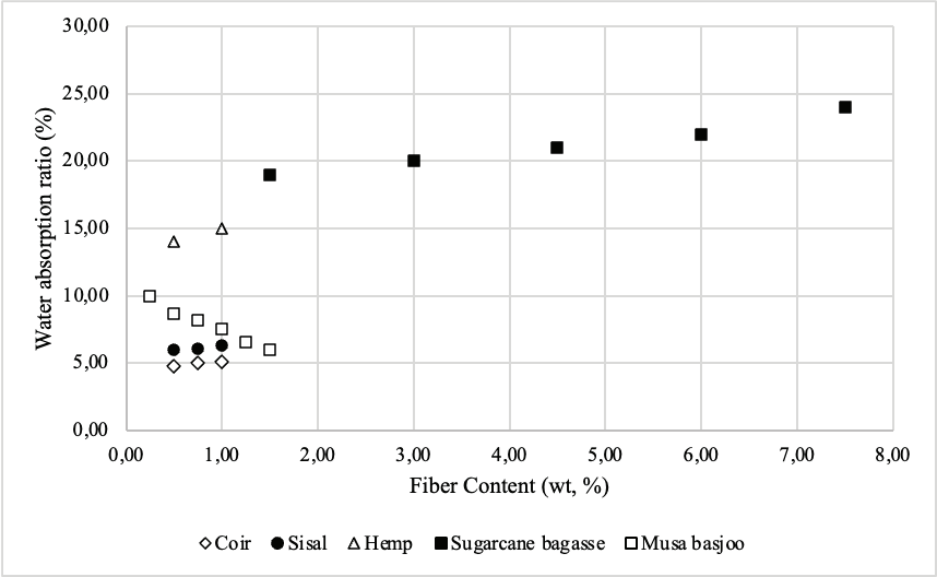


Figure 5. Influence of Plant-Based Fiber Content on the Water Absorption Ratio of Geopolymer Composites, Adopted from Refs. (Poletanovic et al., 2020; Wongsa et al., 2020; Reddy et al., 2022; Yanou et al., 2021)

The hydrophilic characteristics of natural fibers and the inclusion of air voids into the geopolymers as a result of the fiber's addition are considered to be responsible for the increase in water absorption ratio (Yanou et al., 2021). Water molecules enter a natural fiber-reinforced composite in a moist environment via microcracks and the hydrophilic properties of the fiber allow the fiber to absorb this water (Alomayri et al., 2014). Water molecules absorbed onto the hydrophilic groups on plant fibers form a significant number of hydrogen bonds, which form a physical barrier between the matrix and the fiber and result in decreasing the adhesion at the interface (Camargo et al., 2020). As a result, the fibers swell, which may cause microcracks in the material and lead to debonding between the matrix and the fiber. Furthermore, the high cellulose content of plant-based fibers absorbs additional water that enters the interface through these microcracks, causing swelling pressures that induce composite failure (Alomayri et al., 2014). However, unlike other studies, the addition of musa basjoo fibers leads to a decrease in water

absorption ratio from 12.67% to 5.1%. This may be a result of fiber addition creating a dense microstructure (Reddy et al., 2022).

Ultrasonic Pulse Velocity (UPV)

The sound vibrations that can be heard are between 16 and 16,000 Hz. Sound waves with a frequency above 16,000 Hz are called "ultrasound," and these waves are not audible to the human ear. In order for these waves to propagate, the object must be in a solid, liquid, or gaseous state. Otherwise, ultrasound waves cannot propagate through a vacuum. If there is a gap in their orbit, sound waves cannot pass this gap and go around it. This leads to a prolongation of the sound transition time in the material and, thus, a decrease in the sound transmission velocity (Postacıoğlu, 1981).

The porosity-UPV relationship of geopolymer composites is shown in Figure 6.

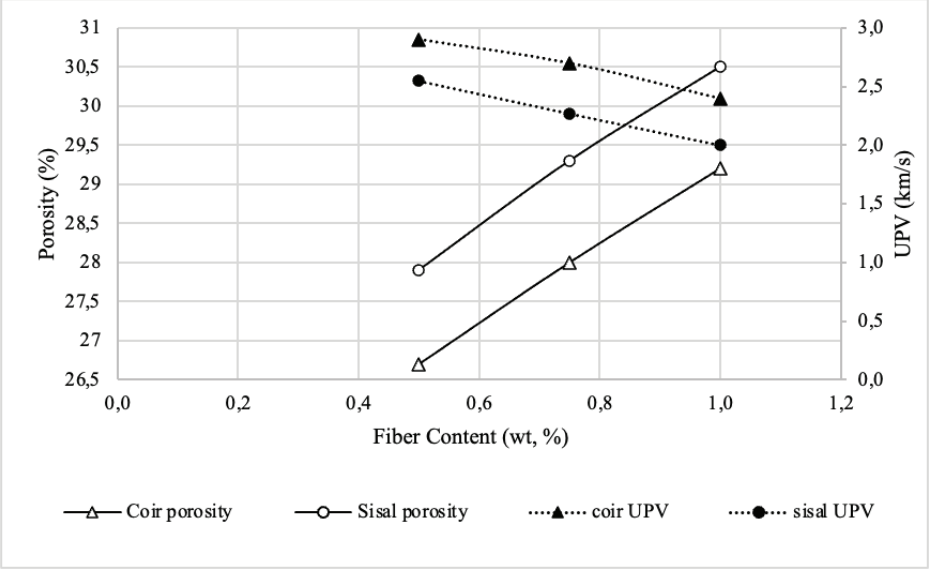


Figure 6. The Porosity-UPV Relationship of Geopolymer Composites Reinforced with Plant-Based Fibers, Adopted from Ref. (Wongsa et al., 2020)

The sisal and coir fiber incorporation increases the porosity compared to the reference sample, and accordingly, the UPV decreases. The

increase in porosity due to the higher fiber contents in sisal fiber samples causes a decrease in UPV until 2.55, 2.27, and 2.00 km/s, respectively. In addition, reinforcing the same geopolymer mortar with the same contents of coir fiber causes the UPV to decrease until 2.90, 2.70, and 2.40 km/h, respectively. As a result, the matrix's porosity really does have a significant impact on the UPV, and air void discontinuities in the matrix can restrict and impede the UPV (Muñoz-Sánchez et al., 2016; Mohammed and Rahman, 2016).

Thermal Conductivity

The thermal conductivity of a material (λ); It is the sum of (i) conduction by solid (λ conduction, solid) and air (λ conduction, air), (ii) convection by air (λ convection), and (iii) radiation between adjacent faces of pores perpendicular to the direction of heat flow (λ radiation) (Ghazi Wakili et al., 2015):

$$\lambda = \lambda_{conduction,solid} + \lambda_{conduction,air} + \lambda_{convection} + \lambda_{radiation}$$

Heat conduction is the primary form of heat energy transfer in solid bodies. Energy spreads by being transferred from one molecule to another as a result of the vibration of the molecules. For a porous material, conduction is the main type of heat transfer (Prud'homme et al., 2015) and $\lambda_{conduction,solid}$ is responsible for the majority of the heat conduction at ambient temperature (Ghazi Wakili et al., 2015). Hence, the thermal conductivity of materials is a function of the ratio between the solid and air amounts of the material (i.e., the total porosity) (Dhasindrakrishna et al., 2021). Generally, porous materials with high porosity or low density have a lower λ value (Liu et al., 2014; Huang et al., 2018; Cui et al., 2018; Bai et al., 2019). Because the thermal conductivity of inert air (0.026 W/mK) is lower than that of the surrounding solid geopolymer matrix (usually 1.0-1.2 W/mK) and the higher porosity of the material means it has more voids that can serve as thermal insulation (Prud'homme et al., 2015). Since low thermal conductivity is equivalent to high insulation capacity (Azimi et al., 2016), the resistance to heat transfer increases as the thermal conductivity coefficient of the material decreases (Davraz et al., 2020).

The influence of plant-based fiber content on the thermal conductivity of geopolymer composites is shown in Figure 7. The thermal conductivity of sugarcane bagasse fiber-reinforced geopolymer (with 7.5 wt% fiber content) decreases to 0.55 W/mK compared to that of the unreinforced matrix (0.77 W/mK) (Nkwaju et al., 2019). The low thermal conductivity of bagasse fibers (0.08 W/mK.), the existence of pores in the geopolymer matrix, which reduce the heat transmission rate due to the lowest thermal conductivity of the air contained in these pores, and the existence of further pores at the fiber-matrix interface all contribute to decreasing thermal conductivity. (Nkwaju et al., 2019). The thermal conductivity of sisal (0.984–1.025 W/mK) and coir (0.949–0.976 W/mK) fiber-reinforced mortars also decreases with increasing fiber contents (Wongsa et al., 2020). The decreasing trend of thermal conductivity of all specimens is also consistent with the increasing trend of porosity and density, as shown in Figures 3 and 4.

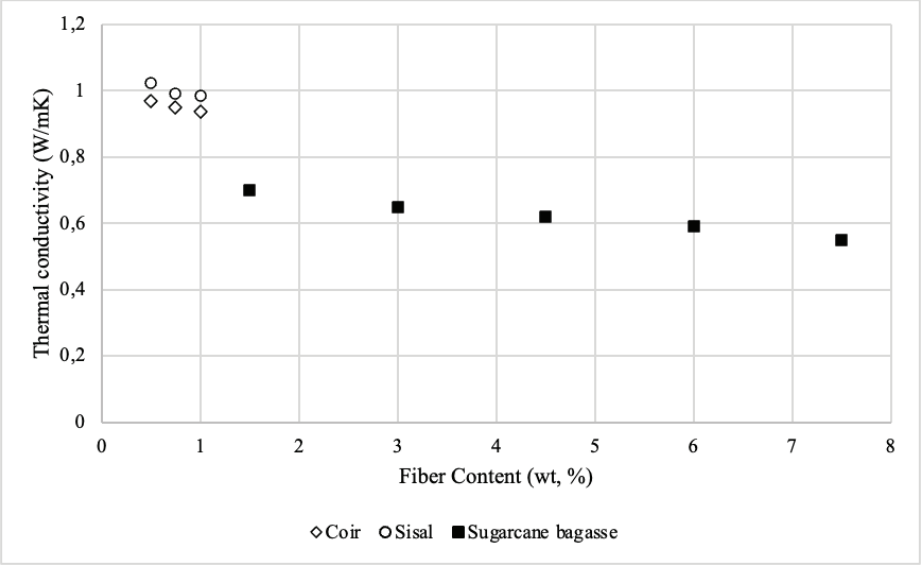


Figure 7. Influence of Plant-Based Fiber Content on the Thermal Conductivity of Geopolymer Composites Adopted from Refs. (Wongsa et al., 2020; Nkwaju et al., 2019)

MECHANICAL PROPERTIES of PLANT-BASED FIBER-REINFORCED GEOPOLYMER COMPOSITES

Flexural Strength

The flexural test is an indirect tensile test that evaluates the geopolymer's resistance to failure under bending. Usually, three- and four-point loading is applied during flexural tests (Abbas et al., 2022). The mechanical resistance of a geopolymer matrix to bending loads and the energy absorption capacity are generally improved by the incorporation of fibers (de Azevedo et al., 2021). For the development of the flexural strength, the fibers' capacity to act as bridges between the cracks and restrict the growth of those cracks is very crucial. Once a crack occurs, the strength of the composite decreases, and the fibers receive bending stresses from the matrix. When a crack contacts a fiber, a specific quantity of energy is required in order to separate the fiber from the matrix, overcome adhesion, and cause crack propagation throughout the matrix. The fiber may be destroyed or separated (pulled) from the matrix during this procedure. Because of the further energy required to break the friction between the fiber and the matrix, the maximum improvement in flexural strength happens only when fiber is pulled from the matrix (de Azevedo et al., 2021). The "bridge effect" distributes the stress to different parts of the composite, preventing it from breaking suddenly. New cracks develop when the material's capacity has been again surpassed by stresses in other regions, and the process repeated. Despite the presence of many additional secondary cracks, there is an active crack that continues to grow and leads the sample to fracture (de Azevedo et al., 2021).

The influence of plant-based fiber content on the flexural strength of geopolymer composites is shown in Figure 8.

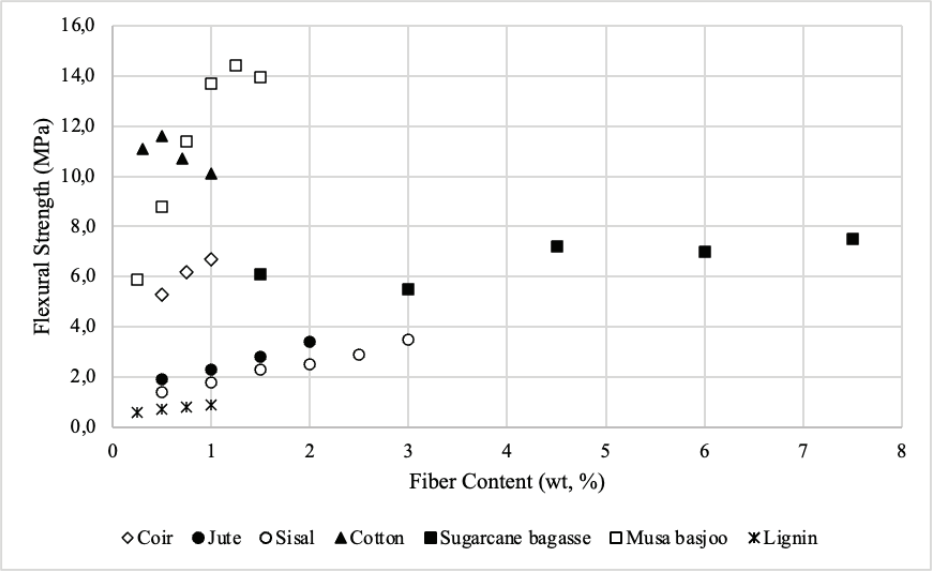


Figure 8. Influence of Plant-Based Fiber Content on the Flexural Strength of Geopolymer Composites, Adopted from Refs. (Silva et al., 2020; Poletanovic et al., 2020; Wongsa et al., 2020; Su et al., 2019; Reddy et al., 2022; Alomayri and Low, 2013; Nkwaju et al., 2019)

The flexural strength of fly ash and slag-based unreinforced geopolymer mortar (0.5 MPa) increases with increasing lignin fiber content (from 0% to 0.25, 0.50, 0.75, and 1.0 %) up to 1.0 MPa (Su et al., 2019). In a different study, the flexural strengths of the unreinforced specimens (5.55 MPa) and those reinforced with the addition of (1 wt%) of coir (5.25 MPa), cotton (5.85 MPa), or sisal fibers (5.90 MPa) are essentially comparable. However, due to the absence of cohesion between the raffia fibers and the matrix, the addition of the raffia fibers results in a 0.55 times lower flexural strength than that of the unreinforced geopolymer (Korniejenko et al., 2016).

In comparison to the unreinforced specimen, geopolymers reinforced with jute and sisal fibers demonstrate better flexural strength. With 2% of jute fibers as the fiber content, the greatest flexural strength of 3.3 MPa is attained; this is an increase of 4.1 times over the unreinforced geopolymer matrix. On the other hand, the geopolymer matrix's

flexural strength increases by 4.3 times with the inclusion of 3% sisal fibers, reaching 3.5 MPa (Silva et al., 2020). In a different investigation, the increasing of fiber content increases the flexural strength of the Musa basjoo fiber-reinforced ash-based geopolymers. The samples with 1.25% fiber content provide a maximum flexural strength of 14.39 MPa. When the plant-based fibers sustain additional stress, they are good at resisting both initial cracks and their development. Over 1.25% fiber content, a 0.95-times reduction in flexural strength is detected. When there are too many fibers in the matrix, the gap between the fibers narrows and agglomerates are formed. As a result of the production of agglomerates, the bond between the fiber and the matrix becomes weaker. This could be the cause of the reduced flexural strength in the specimens with fiber contents greater than 1.25% (Reddy et al., 2022). A similar result is obtained in another study. The flexural strength of cotton fiber-reinforced geopolymer first increases until the fiber content reaches 0.5 %. The efficient distribution of the fibers inside the matrix, which promotes increased adhesion at the matrix-fiber interface, may be responsible for the improvement in flexural strength. As a result, the stress transmission from the matrix to the fibers may function at its optimum, which enhances the strength. However, when cotton fiber concentration exceeds 0.5 wt%, the homogeneity of the composite is prevented, causing agglomerations that weaken the interfacial adhesion between the fiber and the matrix. As a result, the flexural strength decreases (Alomayri et al., 2013). In another research, the incorporation of sisal and coir fibers (0.5%, 0.75%, and 1.0%) into high-calcium fly ash-based geopolymers results in increased flexural strength. This is caused by the fiber's high tensile strength and elasticity modulus, as well as the fact that the fiber's interaction with the matrix allowed for the transfer of stress from the matrix to the fiber. The maximum fiber content is set at 1% volume fraction because fiber contents higher than that have poor workability and made mixtures difficult to cast and compress (Wongsa et al., 2020). Only one study's results differ from those of the others. Flexural strength in laterite-based geopolymers does not appear to be significantly correlated with sugarcane bagasse fiber contents (1.5%, 3%, 4.5%, 6%, and 7.5% wt). The fibers' irregular orientation is probably the reason. According

to research, fibers with a particular orientation (horizontal or vertical) may absorb and evenly distribute the stress all across the matrix (Nkwaju et al., 2019).

Compressive Strength

Compressive loads lead to inelastic volumetric dilatancy in the brittle materials and cause the development of axially splitting microcracks that run parallel to the direction of the applied load. The formation of transversal tensile stress at the crack tips of these microcracks aids in its propagation in the load direction, causing local cracks. Around "weak areas," such as large voids or pores, these local fracture points occur significantly more readily. The compressive stress response of brittle materials is controlled by their density, pore structure, brittleness, and microcrack distribution (Farhan et al., 2021).

Conflicting findings on the compressive strength of fiber-reinforced geopolymer composites have been reported in the literature. Studies show that fibers do not always result in a reduction in the compressive strength and frequently enhance the compressive strength of geopolymers, despite the fact that using fibers is intended to induce an increment in ductility and prevent crack propagation instead of improving the compressive strength (de Azevedo et al., 2021).

The influence of plant-based fiber content on the compressive strength of geopolymer composites is shown in Figure 9.

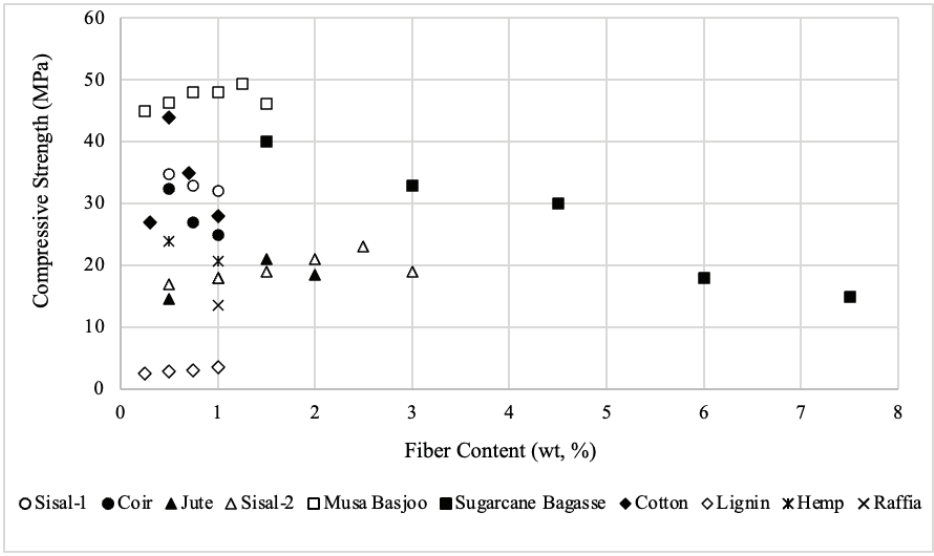


Figure 9. Influence of Plant-Based Fiber Content on the Compressive Strength of Geopolymer Composites, Adopted from Refs. (Silva et al., 2020; Poletanovic et al., 2020; Wongsa et al., 2020; Su et al., 2019; Reddy et al., 2022; Alomayri and Low, 2013; Yanou et al., 2021)

Fly ash and slag-based unreinforced geopolymer mortar's compressive strength (2.4 MPa) improves with higher lignin fiber content (from 0% to 0.25, 0.50, 0.75, and 1.0%), up to a maximum of 3.5 MPa (Su et al., 2019). The results of the compressive strength tests reveal that adding cotton, sisal, and coir fibers (1 wt%) increase the compressive strength of the unreinforced fly ash-based geopolymer by 1.15, 1.05, and 1.26 times, respectively. The absence of adhesion between the raffia fibers and the matrix, however, results in the reinforced matrix's compressive strength being 0.55 times lower than that of the unreinforced matrix (Korniejenko et al., 2016). When compared to the unreinforced geopolymer, specimens reinforced with jute and sisal fibers show improved compressive strength. When the fiber content in jute fiber is 1.5% by weight, the maximum compressive strength is 20.6 MPa, which is an increase of 1.75 times above the reference specimen. When the fiber content is 2.5% by weight, sisal fiber-reinforced geopolymers achieve a maximum compressive strength of 22.1 MPa, an increase of 1.84 times over the reference spec-

imen. Higher fiber contents cause a decrease in compressive strength for both types of fiber-reinforced specimens (Silva et al., 2020). Similar results are also obtained in another study. The compressive strength of the Musa basjoo fiber-reinforced ash-based geopolymer increases with the higher fiber content. Because fibers increase the cohesive force and strengthen the interlocking between aggregates, respectively. Hence, providing a stronger bridging effect and preventing crack development may subsequently result in increased strength (Reddy et al., 2022).

The compressive strength, however, decreases by 0.93 times over 1.25% fiber content. When there are too many fibers, the distance between each fiber decreases, and the bond between the fibers and matrix weakens. Additionally, too many fibers cause the balling effect, which reduces the fiber bridging action (Reddy et al., 2022). The trend in the results is consistent with another study. Following the introduction of 0.5 wt% cotton fibers, the geopolymer's compressive strength improves from 19.1 to 46.0 MPa. This is explained by the probability that more loads are transmitted from the matrix to the fibers, increasing the load carried by the fibers. Good fiber dispersion inside the matrix, which enhances the bonding strength between the fiber and the matrix, may also be a factor in this positive behavior. The compressive strength, however, decreases with the higher contents of cotton fibers (0.7 and 1.0 wt%). The loss in compressive strength may be caused by a greater tendency for these fibers to ball up and form pores in the matrix (Alomayri and Low, 2013). Sisal and coir fibers result in an increment in the compressive strength until 0.5% fiber content in high calcium fly ash geopolymer mortars. However, as the fiber concentration is increased beyond 0.5%, the composite's density decreases, lowering its compressive strength. High fiber content makes the matrix difficult to pack and causes the sample's porosities to increase, which reduces its compressive strength (Wongsa et al., 2020). On the other hand, in some studies where geopolymer mortars are reinforced with various plant-based fibers, the compressive strength may tend to decrease. For instance, it is examined how the inclusion of fibers from alkali-treated sweet sorghum affected the mechanical performance of geopolymers made from fly ash. When the fiber contents are 1, 2, and 3%, the compressive strength decline by

9, 17, and 26%, respectively (Chen et al., 2014). In the other research, the addition of sugarcane bagasse fibers decreases the compressive strength of the laterite-based geopolymers. When the geopolymers are reinforced with 1.5, 3, 4.5, 6, and 7.5% fiber contents, respectively, the compressive strength decreases by 18.3, 31.8, 431, 65.9, and 71.8% in comparison to the unreinforced geopolymer. Higher void content in the composites, which results in weaker zones within the matrix, is responsible for decreasing compressive strength (Yanou et al., 2021). The loss in strength may also be brought on by the orientation of the fibers. Because the fibers are distributed randomly, this may lead to low-stress transmission in the matrix, which will reduce its strength (Nkwaju et al., 2019).

Impact Strength

Impact strength is the quantity of energy that a material may endure when the load is abruptly applied on the material. It can also be described as the amount of force per unit area that must be applied before a material fracture. The bonds at the matrix and fiber interface and the characteristics of the matrix and the fibers control the impact strength of a fiber-reinforced material. As the composites experience an abrupt load, the combination of fiber pull-out, fiber rupture, and matrix deformation dissipates the impact energy (Wambua et al., 2003). Whereas there are a lot of findings on the compressive and flexural strengths of plant-based fiber-reinforced geopolymers, there are comparatively few findings regarding this material's impact behavior.

Figure 10 illustrates how cotton fiber content affects the geopolymer matrix's ability to withstand impact loads. The impact strength of the geopolymer paste is increased after 0.5 weight percent cotton fibers are added. The uniform distribution of the fibers within the matrix, which increases adhesion at the matrix-fiber interface, may be responsible for the improvement in impact strength. The impact strength tends to increase with increasing fiber content due to increased fiber pullout and fiber breakage. Better stress transfer from the matrix to the fibers is made possible by this, and consequently the strength increases. Conversely, as the fiber content increases beyond 0.5 wt%, the impact strength decreases. This decrease at higher fiber content is brought about by the

production of voids and fiber coalescence owing to the higher viscosity, which in turn decreases the adhesion of the fiber and matrix (Alomayri and Low, 2013).

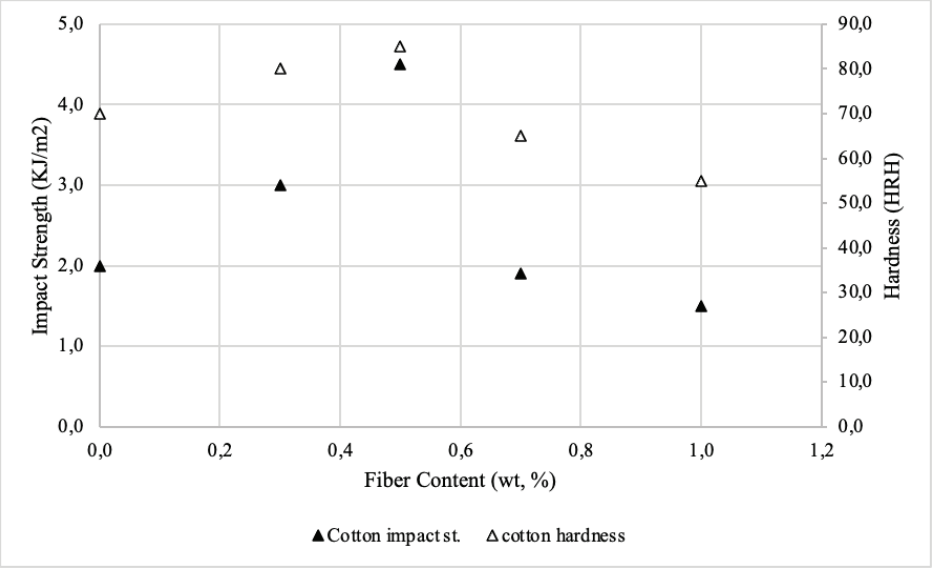


Figure 10. Influence of Plant-Based Fiber Content on the Impact Strength and Hardness of Geopolymer Composites, Adopted from Ref. (Alomayri and Low, 2013)

Hardness

The hardness test is one of the most general mechanical tests performed on the material because it is simple to apply and does not damage the material. In addition, there is a parallel relationship between the hardness of a material and its other mechanical properties, so that an idea can be obtained about the strength values of that material. Hardness is a relative measure and is defined as the resistance of materials to friction, cutting, scratching, and plastic deformation. In scientific terms, it is defined as the resistance of materials to dislocation motion.[2]

Figure 10 shows the impact of cotton fiber content on the hardness of geopolymer composites. The geopolymer with 0.5 wt.% fiber incorpora-

2 Bursa Teknik Üniversitesi Mühendislik ve Doğa Bilimleri Fakültesi Makine Mühendisliği Bölümü, Makine Mühendisliği Laboratuvarı Sertlik Ölçme Deneyi Deney Föyü

tion increases the Rockwell hardness from 70 to 93 in comparison to the unreinforced geopolymer. The considerable increase in hardness is the result of the test load being distributed over the fibers, which decreases the test ball's capacity to penetrate the composite material's surface. However, as the fiber content increases, the hardness decreases because the fibers are poorly dispersed. The incorporation of 0.7 and 1.0 wt.% fibers lead to a decrease in the consistency of the matrix and a low wettability between the fibers and the matrix, so the fibers are easily separated from the matrix. A higher water content in the geopolymer mixture is required to make up for this. In order to solve that problem, increasing water content may result in low hardness (Alomayri and Low, 2013).

Toughness

The amount of energy that a material absorbs during plastic deformation is expressed by its toughness (de Azevedo et al., 2021). Almost all studies on plant-based fiber-reinforced geopolymer composites (Silva et al., 2020; Poletanovic et al., 2020; Alomayri et al., 2013; Ribeiro et al., 2016) show that unreinforced materials with low toughness exhibit abrupt and fragile fracture. However, geopolymers reinforced with plant fiber do not deteriorate after the formation of just a single crack. Usually, fibers carry all of the tensile force in the area where a crack first forms. When the load is increased without rupturing or pulling out the fibers near the existing crack, new cracks will form and the force will be transferred to the fibers at this location. Multiple cracks form as a result of this process, which persists until the fibers break or pull out of the matrix. This mechanism is termed "deflection hardening behavior" and is identified in the load–deflection curve by the strength increases over deflection when the first cracking load is greater compared to the peak load. After the initial crack formation, the composites that show deflection hardening behavior have an increased load-carrying capability and also a higher energy absorption capacity (toughness) (Abbas et al., 2022). Contrary to unreinforced matrix, composites with a higher toughness ensure prolonged ruptures that exhibit signs of emergence, trying to alert to the collapse of the material (de Azevedo et al., 2021). In addition, the higher the plant-based fiber content, the higher the energy absorp-

tion capacity of the plant-based fiber-reinforced geopolymer composites (Poletanovic et al., 2020).

CONCLUSION

This study focuses on a review of the published articles on plant-based fiber-reinforced geopolymer composites. The physical and mechanical properties of randomly oriented short fibers included in geopolymer composites are thoroughly discussed. The conclusions that can be reached are as follows:

- *Various types of plant-based fibers, such as sisal, coir, jute, cotton, hemp, lignin, raffia, pineapple, bamboo, musa basjoo, sorghum, and sugarcane bagasse, can be effectively used as a reinforcement in geopolymer binders, mortars, and concrete. However, the effectiveness of more fiber types, such as banana and palm fibers, on geopolymer composites should also be investigated.*
- *The physical and mechanical properties of geopolymer composites consisting of either artificial (such as fly ash, boiler ash, slag, calcined clay, and fired clay brick powder) or natural (such as natural earth, volcanic earth, and volcanic ash) aluminosilicate sources are significantly impacted by these plant-based fibers.*
- *The type, chemical structure, and properties of the fibers, their content (as a weight percentage (wt%) or volume fraction (vol%)), the manufacturing process, and the curing conditions are important key parameters in order to produce plant-based fiber-reinforced geopolymer composites with higher physical and mechanical properties.*
- *It is crucial to maintain homogeneous dispersion of the fibers and the matrix throughout production since balling and fiber coalescence reduce the required properties.*
- *Plant-based fiber-reinforced geopolymer composites are usually produced with thermal curing between ambient temperature and 90°C for 1 to 24 hours. The optimum curing conditions (curing temperature, duration, and humidity) should be applied, depending on the properties of both the fiber and the aluminosilicate source.*

- *No matter what kind of fiber is used, the workability of fiber-reinforced geopolymers is less than that of the unreinforced geopolymer matrix. The workability of the matrix imposes a limit on the fiber content in order to prevent negative casting conditions brought on by difficulties in molding, vibration, and compacting.*
- *To reduce the viscosity of the geopolymer, more water is added to the matrix. This free water evaporates during temperature curing, leaving a large number of pores in the microstructure. Thus, with the inclusion of fibers, the porosity and the water absorption ratio of composites increase, whereas the density and the ultrasound pulse velocity (UPV) decrease. The porosity has a significant impact on the density and UPV results.*
- *The thermal conductivity of the unreinforced geopolymer matrix decreases after fiber inclusion because of the higher porosity of the composite, the presence of additional pores at the fiber-matrix interface, and also because of the lower thermal conductivity of the plant-based fibers. Therefore, it may be stated that incorporating plant-based fibers may enhance a material's insulating properties.*
- *In general, the flexural, compressive, and impact strengths of unreinforced geopolymers increase with increasing fiber content up to the optimum level. At the optimum fiber content, the fibers are uniformly distributed in the matrix, adhesion at the matrix-fiber interface is good, stress is transmitted from the matrix to the fibers, the fibers can resist both initial cracks and their development, and consequently the mechanical properties improve. However, more fiber incorporation beyond the optimum content causes balling and coalescence of the fibers and creates voids in the matrix that weaken the interfacial adhesion between the fiber and the matrix and, finally, reduce the mechanical properties.*
- *Contrary to unreinforced matrix, plant-based reinforced geopolymer composites have a higher energy absorption capacity which ensure prolonged ruptures that exhibit signs of emergence, trying to alert to the collapse of the material.*

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GÜVEN PLUS GRUP A.Ş.

İLGİLİ MAKAMA

KONU : Güven Yayıncılık A.Ş.

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AÇIKLAMA : 2019 Yılında YÖK tarafından yayınlanan akademik teşvik kriterleri ile ÜAK tarafından yayınlanan doçentlik kriterleri doğrultusunda Güven Yayıncılık A.Ş. Kültür ve Turizm Bakanlığı İstanbul Valiliği İlk Kültür Turizm Müdürlüğü tarafından 36934 Sertifika numarası ve İstanbul Valiliği İl Kültür ve Turizm Müdürlüğü İstanbul Basma Yazı ve Resimleri Derleme Müdürlüğü tarafından Sayı: 37666426-207.01[207.02.02]-E.62175 21.01.2019 tarihli yazısı ile yayın evimiz uluslararası yayın evi kategorisinde olup, 2010 yılı itibari ile 2019 YÖK akademik teşvik kriterleri kapsamında her türlü koşul ve şartı karşılamaktadır. Yukarıda sayı ve tarihi belirtilen belge ilgili yayınevimiz tarafından yayınlanan tüm basılı ve online olan (PDF) kitap jeneriklerinde bu bilgilere yer verilmiştir. Ayrıca 2010 yılı itibari ile yayınevimiz tarafından 20 ve üzerinde yabancı dilde yayınlanmış farklı dünya ülkelerinden yazarlara ait kitaplara dair bilgiler ekte sunulmuştur. Ekte bulunan kitap bilgileri T.C. KÜLTÜR BAKANLIĞI tarafından teyit edilebilir. Yayınevimiz tarafından çıkarılmış olan son on yıla ait kitap sayı ve bilgilerine dair resmi KÜLTÜR BAKANLIĞI yazısı ilgili kitap yazarlarına fotokopi olarak elden (mail) yolu ile teslim edilmiştir. İşbu belge yazar(lar) tarafından talep edilmesi üzerine kendilerine elden (mail) üzerinden teslim edilmiştir. Güven Plus Grup Danışmanlık A.Ş. ve Güven Yayıncılık A.Ş. Kişisel Verilerin Korunması Kanunu kapsamında hareket eder ve bu kanun hükümlerine göre işleyişini devam ettirir. Tarafınıza gönderilen bu bilgiler akademik teşvik kriterleri kapsamında kullanılması adına tarafınıza tahsis edilmiştir. Farklı amaç ve nedenlerle kullanılması durumunda her türlü hukuki hakkımızı maddi ve manevi yönden saklı tuttuğumuzu tebliğ ederiz. Yayınevimiz ekte sunulan uluslararası kütüphaneler tarafından taranmaktadır. Yukarıda tarih ve sayısını verdiğimiz KÜLTÜR BAKANLIĞI resmi yazısında da durum izah edilmiş ve ekte ilgili belge sunulmuştur. Ayrıca http://www.millikutuphane.gov.tr/electronicresource linkten de bu uluslararası kütüphane bilgilerine ulaşabilirsiniz. Kişisel verilerin korunması kanununa aykırı hareket ve taleplere cevap verme yükümlülüğümüz bulunmamaktadır. İlgili kurum ve kurullara arz / rica olunur.

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İkitelli V.D.: 454 031 7918 Mersis No: 0451 0317 9180 0010
Tel:+90 0212 801 40 61-63 Faks:+90 212 801 40 62

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