buildings

Article

Effects of Jute Fiber on Fresh and Hardened Characteristics of Concrete with Environmental Assessment

Muhammad Basit Khan [1,*], Nasir Shafiq [1], Ahsan Waqar [1], Dorin Radu [2], Ciprian Cismaș [2], Muhammad Imran [3], Hamad Almujibah [4] and Omrane Benjeddou [5]

1 Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, Tronoh 32610, Perak, Malaysia; nasirshafiq@utp.edu.my (N.S.); ahsan_21002791@utp.edu.my (A.W.)
2 Faculty of Civil Engineering, Transilvania University of Brașov, Turnului Street 5, 500152 Brasov, Romania; dorin.radu@unitbv.ro (D.R.); c.cismas@unitbv.ro (C.C.)
3 Department of Civil Engineering, Sir Syed University of Engineering and Technology, University Road, Karachi 75300, Sindh, Pakistan; dr.mimran@ssuet.edu.pk
4 Department of Civil Engineering, College of Engineering, Taif University, P.O. Box 11099, Taif City 21974, Saudi Arabia; hmujibah@tu.edu.sa
5 Department of Civil Engineering, College of Engineering, Prince Sattam bin Abdulaziz University, Alkharj 16273, Saudi Arabia; benjeddou.omrane@gmail.com
* Correspondence: muhammad_21002014@utp.edu.my

Abstract: Concrete is a widely utilized construction material globally; however, it is characterized by a fundamental deficiency in its tensile strength when it is not reinforced. The incorporation of diverse novel materials into concrete is being pursued with the aim of mitigating its limitations while concurrently enhancing its reliability and sustainability. Furthermore, it is noteworthy that concrete embodies a significant quantity of carbon. The primary cause of this phenomenon can be attributed to the utilization of cement as the principal binding component in concrete. Recent advancements in research have indicated that jute fiber, commonly referred to as JF, exhibits considerable potential as a novel material for enhancing the mechanical robustness of concrete. Although there is a significant body of literature on the application of jute fiber in concrete, there has been a dearth of research on the capacity of jute fiber (JF) to improve the mechanical strength of concrete and mitigate its carbon emissions. This study aims to cover a gap in the existing literature by analyzing and enhancing the application of JF in relation to its mechanical properties and environmental impact. The study involved conducting experiments wherein JF was added at varying weight percentages, specifically at 0%, 0.10%, 0.25%, 0.50%, and 0.75%. The investigation encompassed a number of examinations of both the fresh and hardened states of concrete, in addition to assessments of its durability. The fresh concrete tests included the slump test, while the hardened concrete tests involved measuring compressive strength (CS), split tensile strength (STS), and flexural strength (FS). Additionally, the durability tests focused on water absorption (WA). The study involved the computation of embodied carbon (EC) ratios for various mix combinations. The findings suggest that incorporating JF into concrete results in a decrease in environmental impact relative to alternative fiber types, as demonstrated by a rise in eco-strength efficiency (ESE). Based on the findings of the conducted tests, an optimal proportion of 0.10% JF has been determined to be conducive to enhancing the CS, STS, and FS by 6.77%, 6.91%, and 9.63%, respectively. The aforementioned deduction can be inferred from the results of the examinations. Using data obtained from extensive experimentation, the RSM (Response Surface Methodology) was used to construct a model. The model was optimized, resulting in the establishment of definitive equations that can be used to evaluate the effects of incorporating JF into concrete. Potential benefits have been identified for the advancement of concrete in the future through the utilization of JF.

Keywords: jute fiber; compressive strength; split tensile strength; flexural strength; embodied carbon; eco-strength efficiency; water absorption; response surface methodology; optimization

Citation: Khan, M.B.; Shafiq, N.; Waqar, A.; Radu, D.; Cismaș, C.; Imran, M.; Almujibah, H.; Benjeddou, O. Effects of Jute Fiber on Fresh and Hardened Characteristics of Concrete with Environmental Assessment. *Buildings* **2023**, *13*, 1691. https://doi.org/10.3390/buildings13071691

Academic Editor: Rajai Zuheir Al-Rousan

Received: 30 May 2023
Revised: 27 June 2023
Accepted: 28 June 2023
Published: 30 June 2023

1. Introduction

Concrete is the most popular building material worldwide [1]. However, its applicability is limited by its susceptibility to low tension, its poor capability to resist the formation of fissures, and its low fracture strain capacity [2]. Fiber-reinforced concrete (FRC) is sometimes viewed as a viable option to compensate for the brittleness of conventional concrete (increased tensile strength). Weak matrices can be reinforced with fiber [3,4]. Numerous studies have shown that adding fibers to concrete substantially improves its properties. In accordance with the American Concrete Institute (ACI), slender fibers reduce plastic shrinkage fractures more effectively than dense fibers [5]. Microfibers with micron-sized diameters have a greater surface area, making them highly efficient at preventing plastic shrinkage fractures in concrete [6]. The incorporation of fibers reduces the permeability and leakage of concrete [7].

The components of concrete can be reinforced with a variety of fibers, both organic and inorganic. Various factors such as the composition, length, elastic modulus, and surface of the fibers are taken into account while selecting the appropriate type of fiber to enhance the tensile strength of concrete [8]. In addition, it is unknown to what extent a fiber might influence the performance of concrete. Metallic and nonmetallic fibers are the two categories commonly used to classify fibers [9]. The ability to conduct electricity distinguishes metallic fibers from nonmetallic fibers [10]. The majority of metallic fibers consist of steel, whereas nonmetallic fibers can be produced from materials such as glass, propylene, and carbon [5–12]. The majority of scholarly investigations center on fibers composed of carbon, glass, propylene, and steel [13,14]. Nevertheless, the aforementioned fibers are considerably expensive. These fibers are also difficult to acquire. In addition, these fibers are significantly stiffer, which negatively affects the flowability of concrete [15]. Several academic studies have suggested the utilization of natural fibers as a preferable alternative to metallic fibers [8–10].

The utilization of natural fiber-reinforced cement composites has been identified as a viable substitute for economical building construction in emerging economies. Because of their ability to decompose and their environmental sustainability, natural fibers have become widely utilized as reinforcing materials [16]. Such fibers are natural and environmentally benign, two characteristics that make bio composites particularly advantageous [17]. Conversely, natural fibers aid in reducing the release of CO_2 emissions into the atmosphere [18,19]. The aviation, construction, automotive, packaging, architectural, and biomedical sectors are increasingly making use of bio composites. Naturally occurring fibers are comparatively more affordable, durable, and recyclable than their synthetic counterparts [20]. Due to the numerous benefits linked to natural fiber-based bio composites, they have largely supplanted synthetic polymers in various applications. Their extensive accessibility, capacity for biodegradation, low mass, economical expense, and straightforward production are noteworthy benefits [21]. A multitude of natural fiber composites have been suggested by scholars for implementation in diverse technological contexts [22].

It has been discovered that the use of coconut, sugarcane bagasse, Roselle, sisal, hemp, and jute increases the compressive and tensile strength of concrete composites [15,16,23]. According to the study's findings, the inclusion of Roselle fiber into the matrix of cement increased its CS and TS (tensile strengths) [24]. The organic fiber reinforcement improves the cement matrix's capacity to absorb energy, thereby transforming the material from brittle to ductile [25]. It is believed that natural fibers introduced as reinforcing agents in cementitious or cement-based composite materials will operate as fissure arrestors and inhibit the propagation of fractures, ultimately resulting in less catastrophic damage. Utilizing continuous fiber reinforcement has led to the formation of a novel kind of construction material with enhanced tensile strength and flexibility [26]. Integrating fiber reinforcement into matrices is essential for improving both durability and toughness. It has been discovered that natural filaments serve as reinforcement agents by bridging matrix spaces and transmitting stresses into them, thereby preventing the formation of microscopic fractures in synthetic materials [27]. Considering the circumstances, the utilization of cement composites reinforced with natural fibers is exceedingly suitable for diverse applications. The aforementioned applications encompass the development of cementitious roofing and ceiling boards with reduced weight, gypsum-based wall materials, and economical construction products suitable for residential buildings. Furthermore, they possess all the requisite attributes that render them highly suitable contenders for the position of foundational structures in industrial machinery. The utilization of jute fiber (JF) in concrete has attracted significant attention, as evidenced by the existing body of research.

The integration of jute fibers (JF) in concrete composites has been considered as a feasible substitute owing to their abundant availability and cost-effectiveness, as they are derived from annual plants [28]. The reason for the abundance of jute fibers is due to their widespread availability. The featured design of these objects comprises either a pentagonal or a hexagonal cross, rendering them a suitable choice for outdoor usage owing to their shielding and UV ray protective properties, as well as their antibacterial characteristics [29]. Because of their exceptional mechanical properties, jute textiles are ideally suited to act as reinforcements in laminated and bionic composites. Jute fabrics have diverse applications. The jute fabric-reinforced composites exhibit satisfactory structural characteristics that conform to the criteria for industrial materials, and they are also financially feasible [30]. Jute is a noteworthy biodegradable natural fiber owing to its exceptional specified properties, economical cost, ample availability, and environmentally friendly nature. In contrast to the inherent mechanical qualities of coconut and sugarcane fibers, the inherent mechanical properties of jute and sisal fibers are much greater. The manifestation of this phenomenon is readily apparent in the specific materials that have been augmented with these suitable fibers. Based on the results of a research investigation, it has been determined that jute fibers possess a tensile strength that falls within the range of 250 to 300 MPa. This level of strength is deemed adequate for a wide array of applications [16]. In addition, the density of these fibers is roughly seven times less than the density of steel fibers [16]. Numerous investigations have been conducted to examine the ability and impact characteristics of cementitious composites, with particular emphasis on the effects of extended, uninterrupted jute fibers and brief, isolated jute fibers. According to their assertion, the incorporation of jute fibers into concrete results in an improvement in the composite's durability, ability to withstand external forces, and ability to resist cracking. According to multiple studies, jute fibers can be substituted for conventional fibers in concrete materials [31]. The properties of natural fiber-reinforced concrete (NFRC) can be affected by numerous variables, including the type and quantity of fibers used. In addition to the hydrophilic characteristics of the fiber, the amount of fiber and infill used in the composite can alter the characteristics of NFRC. In order to achieve optimal performance and high functionality, composites typically require a substantial proportion of fiber content. The optimal conditions are crucial for the proper functioning of concrete. As previously stated, the impact of fiber content on NFRC characteristics is of utmost importance. Instead of utilizing steel fibers, several researchers concentrated on the use of jute fiber (JF). Steel fiber is also associated with corrosion and thermal expansion issues [16]. However, there is no consensus regarding the use of JF in concrete, making it challenging to determine the significance of coconut fiber. Additionally, some changes can occur in jute fiber over time, as biodegradability is a property of jute fiber. Over time, the degradation of jute filaments can be caused by a variety of factors, including exposure to moisture, alkalinity, and microorganisms that are commonly found in concrete environments. The degradation process has the potential to diminish the mechanical properties of the fiber, including but not limited to its tensile strength and rigidity. The presence of cement is responsible for the alkalinity of concrete. The structural integrity of jute fibers may be compromised by protracted exposure to an alkaline environment. The process of alkaline attack can reduce the tensile strength and structural stability of filaments, ultimately leading to their degradation. Regarding the environmental assessment of jute fiber, its cultivation and processing involve various stages including land preparation, planting, harvesting, retting, and fiber extraction. The carbon footprint of jute fiber production depends on factors such as agricultural practices, energy sources used, transportation, and processing methods. Generally, jute is considered a relatively environmentally friendly fiber due to its low pesticide requirements and ability to grow in diverse climates without the need for excessive irrigation. The embodied carbon factor present in the available literature can be utilized for calculating the carbon footprint.

The previous investigation carried out by Ahmed Jawad et al. [16] found that the introduction of JF resulted in an augmented fibrous surface area, causing a decrease in the fluidity of the concrete. This, in turn, led to an elevation in the abrasiveness of the concrete. It has been determined that the incorporation of 2% JF into concrete can result in an augmentation of the concrete's maximum mechanical strength. In their investigation, it was found that the addition of 2% JF results in maximum increases in CS, STS, and FS. Over a 2% threshold, the composite material's mechanical properties degrade when jute fiber is added to concrete. The incorporation of JF has been observed to enhance the durability characteristics of concrete, specifically with regards to density, water absorption, drying shrinkage, and tolerance to acidic environments.

In one more investigation on the use of JF in concrete, performed by Muhammad S. Islam et al. [32], an observation was made indicating a positive correlation between the augmentation of JF concentration in concrete and the decline in the slump of freshly mixed concrete. The findings indicate that the slump reduction in concrete mixes was more pronounced in specimens containing JF with a greater length and aspect ratio, specifically JF with 20 mm of length and an aspect ratio of 200, compared to those containing JF with a length of 10 mm and an aspect ratio of 100. This phenomenon occurred because the lengthier JF had a significantly greater ratio of surface area to volume. The study's results indicate a correlation between the duration of the curing process and the attained level of CS. The research findings indicate that the addition of a small proportion of 0.25% jute fiber to concrete led to a notable improvement in its compressive strength, regardless of the fiber's length. The findings of this study demonstrate that the specimens subjected to testing for CS, STS, and FS exhibited failure patterns that suggest a reduction in the quantity and dimensions of cracks due to the incorporation of jute fibers. The aforementioned tests were performed on specimens that were confirmed to have been subjected to CS, STS, and FS. As intended, the fibers helped prevent the concrete sample from completely failing. Supplementary cementitious materials and natural fiber such as Jute can be used in concrete, resulting in a reduction in embodied carbon [33].

Limited studies have been performed to analyze the effects of JF on a concrete's fresh and hardened state. Additionally, there is lack of studies regarding the environmental impact (carbon emission) of concrete containing JF. To fill this literature gap, the aim of this study is to evaluate the effect of JF on concrete properties (fresh, hardened, and environmental), develop and analyze statistically sound models, and then improve mortar formulations for the advancement of infrastructure. The objective of this research is to analyze the influence of the JF particle ratio, in combination with other prognostic factors, on the characteristics of newly mixed and solidified concrete compositions that have been developed utilizing RSM. The utilization of this particular technology possesses the capability to expedite the incorporation of fiber-reinforced concrete in a practical environment. This investigation will help promote the practical use of JF in concrete, and will help in predicting the strength of concrete containing various percentages of JF with the aid of statistical equations.

1.1. Design of Experiments (DoE)

Background

Commonly, "DoE" refers to the "design of experiment" method, which is renowned for its effectiveness in managing multiple inputs and facilitating decision-making processes [34]. Various industrial domains and service providers have utilized this methodology to improve the efficacy of assessments [35]. Historically, the OVAT methodology has been employed to tackle issues that involve numerous variables by holding all elements constant, except for one, and conducting iterative trials until the most favorable outcomes are achieved for the variable under investigation [36]. The iterative technique is carried out for every variable until the desired result is attained, taking into account the multiple factors involved in the problem. Although the method is characterized by its straightforwardness and precision, it requires a significant amount of data and a sequence of expensive and laborious experiments [37]. The aforementioned aspect holds significant importance within the realm of research pertaining to building materials, specifically concrete. In contrast to previous research, which focused exclusively on a single response variable, namely the effect and quantity of replacement material on concrete properties, the present investigation aims to comprehensively investigate all response variables [38].

The effectiveness of high-strength and self-consolidating concrete is impacted by a complex array of interrelated variables [39]. The aim of employing the DoE methodology is to minimize the quantity of data essential for mathematical simulation by segregating the effect of individual variables on the dependent parameter of concern. The abundance of DoE analyses could potentially pose a difficulty for scholars who lack pertinent domain expertise and a well-defined approach for addressing issues [40]. The DoE has been efficiently employed in the examination of building materials in contemporary times. DoE has been widely employed in various stages of concrete research, ranging from predicting concrete strength to generating concrete design combinations. Numerical equations are sometimes necessary to evaluate the strength of ordinary concrete, as nondestructive testing (NDT) results alone may not suffice [41,42].

The conventional approach in this scenario involves the utilization of simple linear regression (SLR) in tandem with a scatter chart [32,33]. Currently, sophisticated evaluation techniques such as the Response Surface Method are used to generate highly accurate and exhaustive forecasts. Particularly advantageous is the application of DoE procedures when identifying suitable substitute materials [36]. A considerable segment of modern literature utilizes a sophisticated approach to examine the outcomes of assessments [43]. The application of DoE methodologies has been employed to assess diverse substitute materials such as tyre rubber [44] and fly ash [45]. Prior research has utilized alternative techniques such as response surface methodology, curve fitting techniques [46], and artificial neural network-based approaches to improve concrete design methodologies that frequently incorporate constituents derived from pervasive environmental waste.

2. Materials and Experimental Methods

2.1. Materials

The experiment employed ordinary Portland cement (OPC) as its primary material; the composition of OPC is presented in Table 1. In addition, the binders used in the study were compliant with ASTM C150M-15 standards. The procurement process of the required materials did not make any compromises in terms of sourcing jute from local suppliers, given its crucial role as a constituent of concrete. By employing the available equipment and following the jute specifications provided by the supplier, an assessment was conducted on the characteristics of the material to ascertain its suitability for the manufacturing of concrete and other related examination processes. Monitoring the growth of jute within concrete and assessing the structural soundness of the jute are crucial steps for enhancing the quality of reinforced concrete elements. The optimal adhesion between jute and concrete facilitates the production of reinforced concrete components with enhanced strength. This ensures that optimal adhesion between the jute and the concrete is attained. The procurement of micro silica was carried out through a local vendor for this intended application, having a specific gravity of 2.23. Subsequently, the material was conveyed and subjected to an assessment of its density and other pertinent characteristics. The research findings indicate a strong correlation between the properties of the material and its reduced WA capacity, coupled with an increased ability to be absorbed by materials possessing a specific particle size or diameter. The selection of the coarse aggregate was made from a vendor in close proximity. The research employed locally available fine aggregate.

The acquisition of a Polycarboxylate superplasticizer (SP) with a density of 1200 kg/m^3 from nearby suppliers enabled the satisfaction of water demands in the manufacturing process of self-consolidating concrete. The process of cross-matching between jute and superplasticizers is commonly employed in order to identify any potentially deleterious chemical constituents that may adversely affect the integrity of the fiber. The composition of JF can be seen in Table 2.

Table 1. Composition of OPC [47].

Composition	Percentages (%)
SiO_2	21.06
Al_2O_3	6.10
CaO	57.98
MgO	2.74
Fe_2O_3	3.08
SO_3	2.40
Loss	4.07

Table 2. Constituents of Jute fiber [48].

S. NO.	Constituents	Percentage (%)
1	α-Cellulose	60.00
2	Lignin	12.00
3	Hemicellulose	22.00
4	Fatty and waxy matter	1.00
5	Nitrogenous matter (as protein)	1.00
6	Miscellaneous	3.00
7	Mineral matter (ash)	1.00

2.2. RSM and Mix Proportioning

The examined concrete was produced in accordance with ACI 211.1-91 [49] specifications, with no jute fiber (controlled samples) [50]. Using Design Expert 13 software and response surface methods, it was possible to formulate compounds containing variable amounts of jute. In order to showcase the influence of the independent variable, jute, on the dependent variable, it is necessary to manipulate it within the framework of RSM. The optimal design selection of the Design Expert (version 13) software was used to implement the Mix Design. Various composite formulations contained between 0% and 0.75% jute. Experiments on freshly mixed and cured concrete, such as evaluations of collapse cone, CS, STS, FS, WA, EC, and ESE, may be relevant to this inquiry. While RSM produced numerous blends with varying proportions of JF, the other components of the mixture gravel, fine sand, micro silica, water, and superplasticizers (SP) remained constant. Table 3 displays the blend proportions for RSM.

Table 3. Mix proportioning.

Mix	Cement (Kg/m^3)	Silica Fumes (Kg/m^3)	Jute Fiber (%)	Fine Aggregate (Kg/m^3)	Coarse Aggregate (Kg/m^3)	Water (Kg/m^3)
JF0%	500	50	0%	600	1000	140
JF0.10%	500	50	0.10%	600	1000	140
JF0.25%	500	50	0.25%	600	1000	140
JF0.50%	500	50	0.50%	600	1000	140
JF0.75%	500	50	0.75%	600	1000	140

2.3. Preparation of Samples

Following a comprehensive mixing process of the dry constituents, comprising cement and aggregates, lasting over two minutes, the addition of water and superplasticizer ensued. The concrete mixture was appropriately homogenized with the aforementioned mixture for a brief duration. The process of jute preparation involved a gradual sprinkling of the material onto a concrete surface. The specimens were fabricated subsequent to the adequate mixing of the concrete. The specimens were gathered in accordance with the directives specified in JIS A 1115 and JIS A 1138, with the objective of carrying out examinations of the flowability of the concrete. The slump of the concrete was determined through utilization of a slump cone, in accordance with ASTM C143 [51]. Upon completion of the precise preparation of the concrete, the process of constructing the specimens could commence. Specimens demonstrating CS and measuring 100 mm in length, 100 mm in height, and 100 mm in width were fabricated in accordance with the prescribed guidelines outlined in ASTM C78/C78M. During the research study, specimens for STS were produced in accordance with the standards outlined in ASTMC496. The dimensions of the specimens were recorded as 100 mm in width and 200 mm in height. The samples were subjected to examination and analysis on the 28th day following their formation. The FS of the specimen was assessed through a standardized test that was carried out in compliance with the guidelines outlined in ASTM C78/C78M-21. On the 28th day subsequent to the casting process, the aforementioned samples underwent rigorous testing in the laboratory. Table 4 displays the codes followed for testing and Figure 1 shows the testing equipment.

Figure 1. (**a**) Sample preparation, Equipment for testing of (**b**) CS (**c**) STS (**d**) FS.

Table 4. Codes followed.

Tests	Codes
Slump	ASTM C143
Compressive strength	ASTM C78/C78M
Split tensile strength	ASTMC496
Flexural strength	ASTM C78/C78M-21

3. Results and Discussion

3.1. Fresh Characteristic

Slump Flow

Figure 2 displays the slump flow of concrete containing JF and the control mix without JF. It can be seen that the control mix with 0% JF has high flowability as compared to mixtures containing JF content. The value of slump flow for the control mix is 85 mm. It was observed that the inclusion of JF has negative effects on the flowability of concrete. The addition of 0.10% JF results in a reduction of flowability by 10.5%. The further inclusion of 0.25% JF in concrete decreases the slump flow by 22.3%. The addition of 0.50% JF reduces the flow of concrete by 41.1% in contrast to the control mix. A maximum reduction of flow was observed following the inclusion of 0.75% JF, which is 54.11% less than the control mix. Given that JF is a hygroscopic material, it is evident that the incorporation of JF reduces droop flow. Hygroscopic materials have the tendency to absorb water; therefore increasing the JF content in concrete decreases the slump flow. Another reason for the reduction in slump can be the very strong bonding and cohesion between cement paste and JF. In the prior study carried out by S. Islam et al. [32], it was revealed that the addition of JF in concrete results in lessening the flowability of the material. According to the research conducted by Rakibul Hasan et al. [52], the inclusion of 0.75% JF in concrete has been found to yield satisfactory results in terms of flowability, though more than 0.50% inclusion of JF in concrete enhances the viscosity and constancy of concrete.

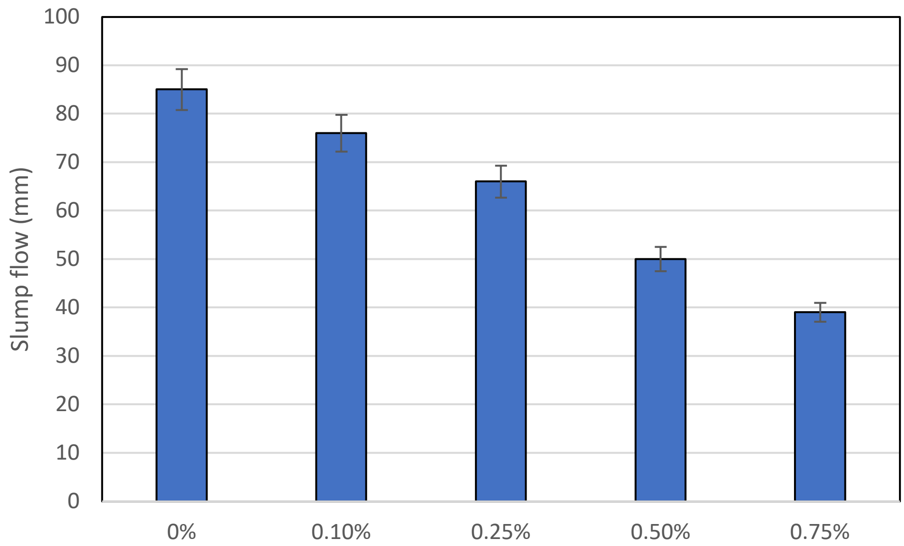

Figure 2. Slump of fresh concrete.

3.2. Mechanical Properties

3.2.1. Compressive Strength

The CS of concrete blended with variable percentages of JF can be seen in Figure 3. The control group lacking the presence of JF exhibits a CS of 59 MPa. The incorporation of JF into concrete exhibits a positive correlation with its CS, up to a certain point, beyond which, the accumulation of JF leads to a reduction in the CS of the concrete. With the inclusion of 0.10% JF in concrete, the CS increases by 6.77%. Further inclusion of 0.25% JF increases the CS by 3.38%. It can be seen that this is the optimum percentage of JF to be added to concrete in this mix. Increasing the content of JF by more than 0.10 reduces the CS. The inclusion of 0.50% JF decreases the strength by 3.39% in contrast to the control sample. The addition of 0.75% JF decreases the strength by 11.86% compared to the control sample. Only a 0.10% addition of JF in concrete leads to the best results in this investigation, in contrast to other mixes with different percentages. In the previous study performed by Mohammad H. Elgawish et al. [53], the inclusion of 0.25% to 0.50% JF in concrete having the length of 18 ± 2 mm enhanced the CS of concrete by 15%. Islam and Ahmed [32], found that adding 0.50% JF, having a length of about 20 mm, enhanced the strength of concrete slightly. The addition of an excessive amount of JF in concrete reduces the CS because an excessive content of JF causes clusters and agglomeration within the concrete mix. The improper mixing or addition of JF causes the evolution of voids in concrete, which leads to a reduction in the concrete's strength. An excessive amount of JF content in concrete also disrupts the cement hydration process, which is also the main reason for the reduction in the CS of concrete.

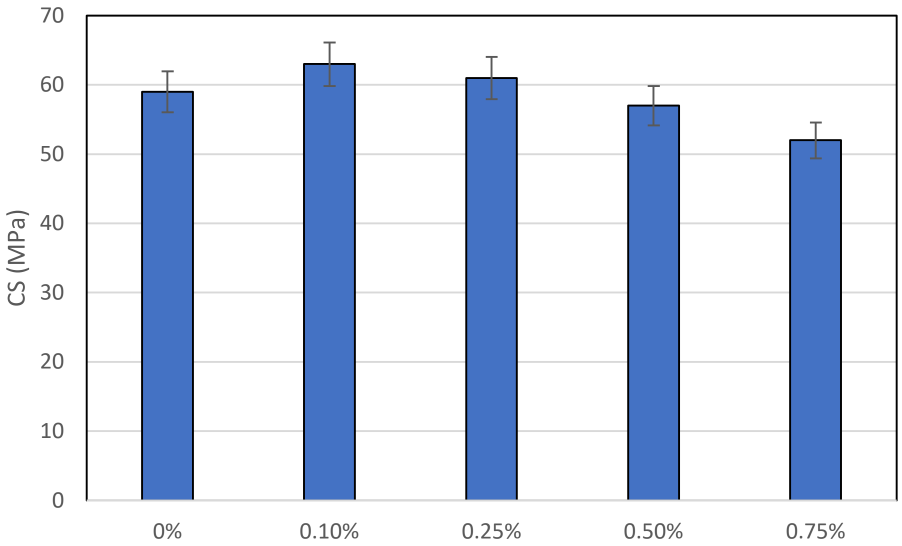

Figure 3. CS of concrete blended with JF on 28th day.

3.2.2. Split Tensile Strength

Figure 4 depicts the STS of concrete. The control sample has an STS of about 5.62 MPa. While the addition of JF in concrete results in an increase of the STS to some extent. The inclusion of 0.10% of JF in concrete increases the strength by 6.91%. While if the percentage of JF is increased to 0.25%, the STS increases by 3.21%. Furthermore, the addition of 0.50% JF results in a decrease of the strength by 1.4%. If the addition of JF is increased to 0.75%, the STS of concrete is reduced by 10.29%. From the investigation, it is clear that a 0.25% addition of JF in concrete is the optimum percentage to be utilized, which increases the strength to the maximum extent. The experimental study carried out by Elgawish and Zakaria [53] found that the addition of 0.10–0.50% JF in concrete with 10–20 mm of length enhances the STS of concrete. Similarly, study carried out by Tiezhi Zhang et al. [54], The optimal percentage range for maximizing the rigidity of concrete is between 0.25% and 0.50% JF fiber, with a length of 18 ± 2 mm. JF increases the toughness of concrete, which allows the concrete to undergo distortion under tensile stresses. The ductile behavior of concrete enhances the STS of concrete. The STS is also improved because of the enhanced adhesion between the cementitious matrix and JF [55].

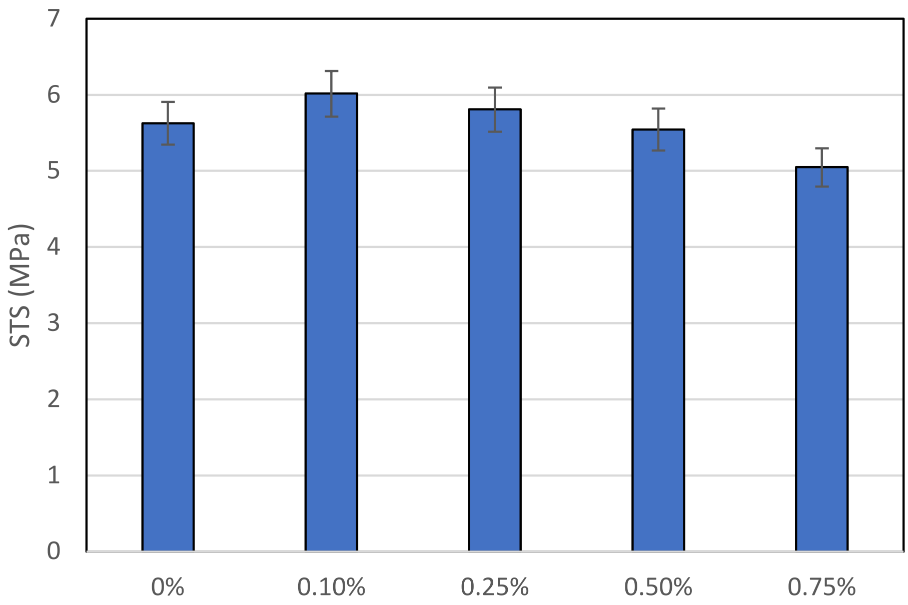

Figure 4. STS of concrete blended with JF on 28th day.

3.2.3. Flexural Strength

The FS of each mix is presented in Figure 5. The data indicate that the control mix possesses a FS of 4.76 MPa. The addition of 0.10% JF raises the FS by 9.63%, while further inclusion of 0.25% JF increases the strength by 5.88%. The data indicate that the inclusion of 0.25% JF in the mixture leads to a decrease in FS in comparison to the mixture containing 0.10% JF. This suggests that the optimal percentage of JF to be added to concrete is 0.10%, as increasing the JF content beyond this threshold results in a reduction in strength. The inclusion of 0.50% JF results in very low increases in FS that are almost equal to the control mix. Increasing the content of JF to 0.75% reduces the FS by 6.95% in contrast to the control sample. The ductility of concrete may be augmented through the incorporation of JF in the concrete matrix, thereby improving its capacity to undergo deformation prior to failure. This results in an increase in the flexural capacity of the concrete. Additionally, fiber acts as a reinforcement in concrete and forms a network in the cement matrix which evenly distributes the applied loads, as well as provides resistance to the loads, due to which, the FS of concrete increases. JF also enhances the bond with cementitious material in concrete, which improves cohesion and transfers the load to the surrounding matrix; this improved bonding increases the FS of concrete. According to the study performed by Islam and Ahmed [32], aside from the addition of 10 mm fiber at a dosage of 0.50%, the addition of jute fiber did not significantly increase the rigidity of the concrete beam's fracture. The utilization of 10 mm fiber at a concentration of 0.50% resulted in a rise of approximately 6.0% in the modulus of rupture. At a fiber length of 20 mm, a decreasing trend in the modulus of rupture was observed across all three evaluated fiber concentrations (0.25%, 0.50%, and 1.00%). According to the results, the amalgamation of JF in a significant percentage of 1.0% demonstrated an adverse influence on the modulus of rupture. This was true independently of whether the aspect ratios of the fibers were 100 or 200. This phenomenon persisted despite variations in the length of the fibers.

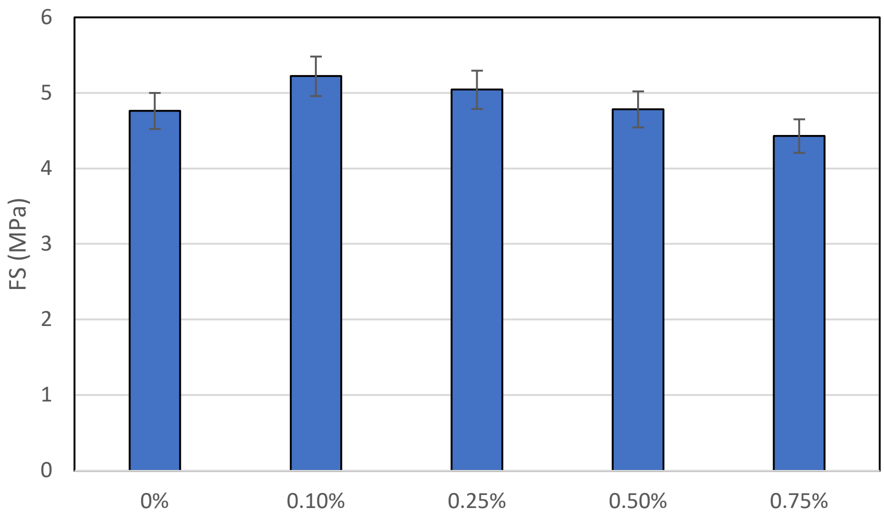

Figure 5. FS of concrete blended with JF on 28th day.

3.3. Durability of Concrete

Water Absorption

Findings about the WA influenced by the addition of JF in concrete are displayed in Figure 6. In comparison to the other ratios, it is evident that the proportion of WA present in the control mixture is significantly less than that observed in any of the other blends. The control mix exhibits a WA percentage of 2.57%. With the addition of JF in concrete, the WA increases because of its properties. With the inclusion of 0.10% JF in concrete, the WA increases by 12.45%. With the addition of 0.25% JF, the WA increases by 20.62%. Furthermore, the addition of 0.50% JF enhances the absorption of water by 36.18%, and the inclusion of 0.75% JF results in an increase of absorption by 46.30%. These results indicate that the addition of JF in concrete and WA are directly related; the absorption of water increases with the rise in JF content. JF is a hygroscopic material in nature, due to which, it can absorb the moisture content from its surroundings. The addition of JF in concrete results in the formation of porous elements within the concrete matrix. Because of this, the WA in concrete is increased, and this increase in WA provides adhesive effects on the concrete strength, increases the permeability, reduces the mechanical strength, and causes durability issues [6]. In the study carried out by Alomayri and Babar [56], the addition of 0.15% to 0.50% JF causes the WA to increase by 16.5%.

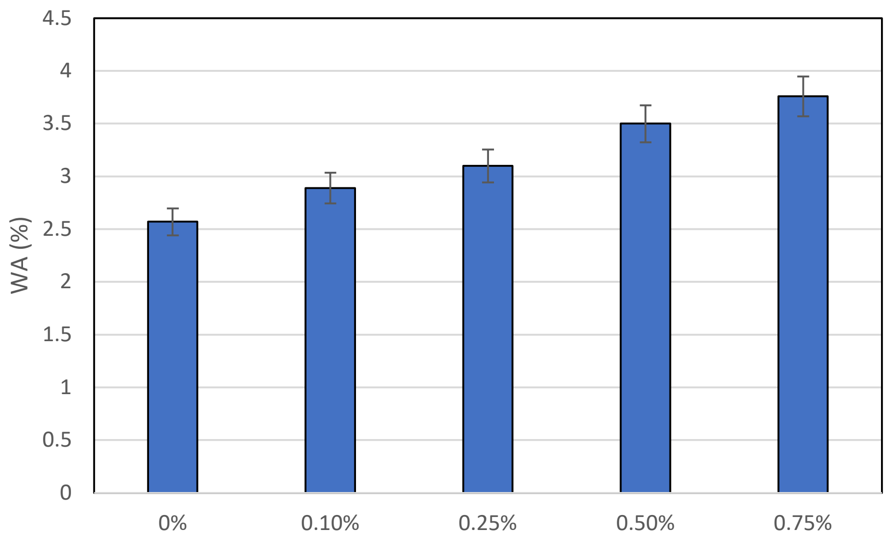

Figure 6. WA of concrete blended with JF on 28th day.

3.4. *Assessment of Sustainability*

3.4.1. Embodied Carbon

For the evaluation of concrete's sustainability, the EC values of each mixture were calculated using the available literature. With the aid of the available literature, the EC factors of each material were determined, and with the aid of these EC factors, the EC values of all proportions containing varying percentages of JF were calculated. The EC factors are listed in Table 5.

Table 5. Factors of EC.

S. NO.	EC Factors	EC Factors CO_2 (Kg/Kg)	References
01	Coarse Aggregate	3.4	[57]
02	Fine Aggregate	0.0139	[58]
03	Water	0	[59]
04	Cement	0.82	[60]
05	Silica fume	0.024	[61]
06	Jute fiber	0.566	[62]

The EC values of all the proportions with varying JF content can be seen in Figure 7. The empirical data suggest that the inclusion of jute fiber has a negligible impact on the EC of the material. However, it should be noted that the introduction of jute fiber does result in a slight increase in EC. The control mix has the lowest EC: 460.34 CO_2 (Kg/Kg). The addition of a very small content of fiber increases the EC slightly. Concrete containing a JF content of about 0.10% has an EC of about 460.623 CO_2 (Kg/Kg). As the quantity of JF increases, the EC also increases. This shows that the EC is directly related to the addition of JF in concrete. Overall, there is not that much difference between the EC of the control mix and the mix containing JF. The maximum EC can be seen with the addition of 0.75% JF in concrete, which is 462.4625 CO_2 (Kg/Kg). JF is the sustainable material to be used in concrete, as per the findings.

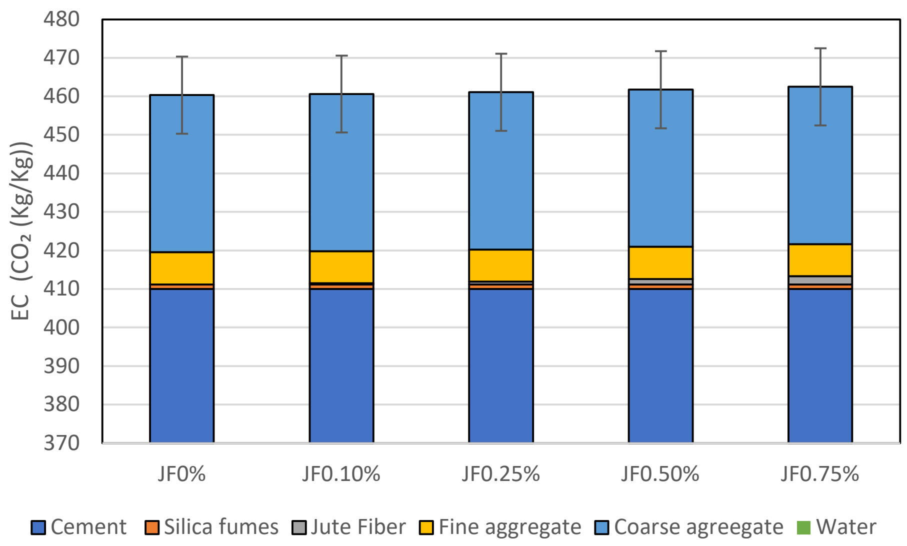

Figure 7. EC of concrete containing JF.

3.4.2. Eco-Strength Efficiency

Though the EC of concrete has been determined for the assessment of concrete's sustainability, concrete cannot be selected only on the basis of sustainability; other factors should also be considered before the selection of the appropriate mix. The ESE of concrete should be determined for the selection of the appropriate mix. The ESE is the ratio between the 28th day CS of concrete and the EC of concrete. The CS of concrete is considered for determining the ESE of concrete, as the CS of concrete is the principal characteristic of concrete. Figure 8 represents the ESE of each concrete mix. The ESE of the reference mixture is observed to be 0.128 MPa/kgCO_2.m^3. The addition of 0.10% JF increases the eco-efficiency by 6.71%. The addition of 0.25% JF to concrete yields a 3.23% rise in ESE, while the introduction of 0.5% JF causes a 3.68% decline in ESE relative to the control group. The addition of 0.75% JF to concrete reduces the eco-strength efficacy by 12.26% compared to the control mix. The concrete mixture containing 0.10% JF has the highest ESE and is more appropriate for use due to its minimal EC and high ESE.

$$\text{ESE} = \frac{28th\ day\ CS}{Embodied\ carbon} \quad (1)$$

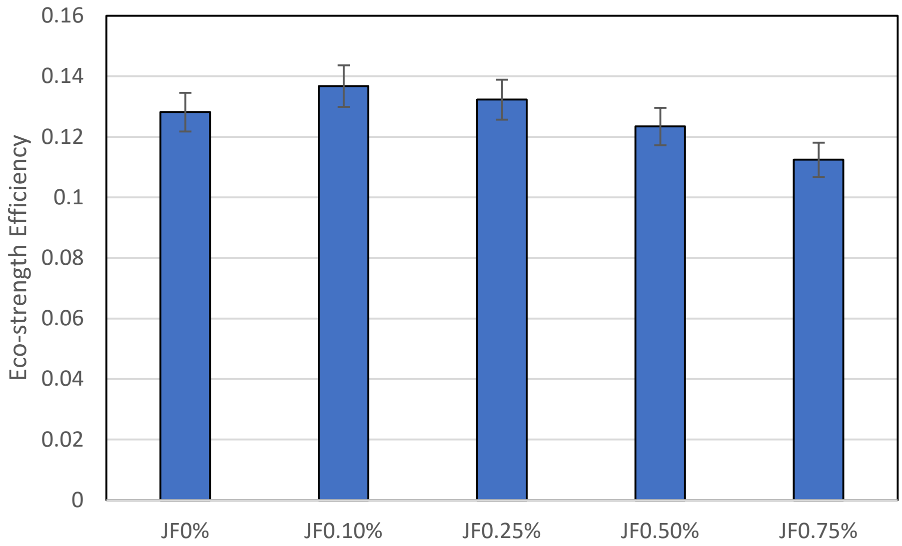

Figure 8. ESE of concrete containing JF.

4. Analysis of Variance Using RSM

As presented in Table 6, the Response Surface Methodology (RSM) model is employed to assess and forecast the impact of jute on the fresh properties and hardened characteristics of concrete. A multiple regression analysis was performed on the experimental data set for RSM. Based on the best design methodology, Tables 5–11 give the results of the ANOVA according to the projected model. The statistical measures of Sum of Squares (SS), F-values of models, and *p*-value are presented at a significance level of 0.05 [63]. Utilizing *p*-values ranging between 0.05 and 0.01, the statistical significance of each individual component is determined [64]. These values indicate a favorable correspondence between the observed values and the expected values. The results of our study's ANOVA point to model *p*-values of 0.005 for the input factor. Tables 7–13 provide the F-values of the RSM-generated model by design expert software for the slump, CS, STS, FS, WA, EC, and concrete's ESE after 28 days of curing. These values are 18,295.35, 108.90, 55.29, 34.60, 1827.77, 9.685×10^6, and 148.03, respectively. This draws attention to the importance of the resulting models. The effectiveness and validity of the model are also assessed using the F value and lack of Fits. The absence of Fits suggests some data variance close to the model fit [65,66]. In cases where the *p*-value is greater than 0.005, there is no statistical evidence to support the existence of a lack of fit.

Table 6. Results of all response variables.

Model Validation Limitations	Slump	CS	STS	FS	WA	EC	ESE
Std. Dev.	0.3284	0.6051	0.0707	0.0713	0.0269	0.0005	0.0012
Mean	63.54	57.92	5.56	4.79	3.15	461.23	0.1252
C.V. %	0.5169	1.04	1.27	1.49	0.8552	0.0001	0.9252
PRESS	1.56	7.04	0.0961	0.0977	0.0099	5.109×10^{-6}	0.000
−2 Log Likelihood	4.53	19.05	−36.77	−36.56	−60.53	−164.72	−143.66
R-Squared	0.9997	0.9732	0.9485	0.9202	0.9973	0.999	0.9801
Adj R-Squared	0.9997	0.9643	0.9314	0.8936	0.9967	0.999	0.9735
Pred R-Squared	0.9996	0.9427	0.8900	0.8295	0.9963	0.999	0.9576
Adeq Precision	291.9249	28.5585	21.1222	17.1756	90.8653	7414.069	32.8631
BIC	12.22	29.31	−26.51	−26.30	−52.83	−154.46	−133.40
AICc	13.20	32.05	−23.77	−23.56	−51.86	−151.72	−130.66

Table 7. Results of the ANOVA for the Variable Response Slump Flow.

Response	Source	Sum of Squares	Df	Mean Square	F-Value	*p*-Value > F	Significance
Slump Flow	Model	3946.15	2	1973.08	18,295.35	<0.0001	significant
	A-JF	3337.02	1	3337.02	30,942.49	<0.0001	
	A^2	46.25	1	46.25	428.86	<0.0001	
	Residual	1.08	10	0.1078			
	Lack of Fit	1.08	2	0.5392			
	Pure Error	0.0000	8	0.0000			
	Cor Total	3947.23	12				

Table 8. Results of the ANOVA for the Variable Response 28-day CS.

Response	Source	Sum of Squares	Df	Mean Square	F-Value	*p*-Value > F	Significance
CS	Model	119.63	3	39.88	108.90	<0.0001	significant
	A-JF	34.73	1	34.73	94.86	<0.0001	
	A^2	36.30	1	36.30	99.15	<0.0001	
	A^3	8.39	1	8.39	22.91	0.0010	
	Residual	3.30	9	0.3662			
	Lack of Fit	3.30	1	3.30			
	Pure Error	0.0000	8	0.0000			
	Cor Total	122.92	12				

Table 9. Results of the ANOVA for the Variable Response STS 28th day.

Response	Source	Sum of Squares	Df	Mean Square	F-Value	*p*-Value > F	Significance
STS	Model	0.8293	3	0.2764	55.29	<0.0001	significant
	A-JF	0.1832	1	0.1832	36.64	0.0002	
	A^2	0.3485	1	0.3485	69.70	<0.0001	
	A^3	0.0334	1	0.0334	6.68	0.0294	
	Residual	0.0450	9	0.0050			
	Lack of Fit	0.0450	1	0.0450			
	Pure Error	0.0000	8	0.0000			
	Cor Total	0.8743	12				

Table 10. Results of the ANOVA for the Variable Response FS of 28th day.

Response	Source	Sum of Squares	Df	Mean Square	F-Value	p-Value > F	Significance
FS	Model	0.5272	3	0.1757	34.60	<0.0001	significant
	A-JF	0.1946	1	0.1946	38.30	0.0002	
	A^2	0.3018	1	0.3018	59.41	<0.0001	
	A^3	0.0812	1	0.0812	15.98	0.0031	
	Residual	0.0457	9	0.0051			
	Lack of Fit	0.0457	1	0.0457			
	Pure Error	0.0000	8	0.0000			
	Cor Total	0.5729	12				

Table 11. Results of the ANOVA for the Variable Response WA.

Response	Source	Sum of Squares	Df	Mean Square	F-Value	p-Value > F	Significance
WA	Model	2.64	2	1.32	1827.77	<0.0001	significant
	A-JF	2.17	1	2.17	2997.85	<0.0001	
	A^2	0.0535	1	0.0535	73.98	<0.0001	
	Residual	0.0072	10	0.0007			
	Lack of Fit	0.0072	2	0.0036			
	Pure Error	0.0000	8	0.0000			
	Cor Total	2.65	12				

Table 12. Results of the ANOVA for the Variable Response EC.

Response	Source	Sum of Squares	Df	Mean Square	F-Value	p-Value> F	Significance
EC	Model	7.72	3	2.57	9.685×10^6	<0.0001	significant
	A-JF	0.6855	1	0.6855	2.580×10^6	<0.0001	
	A^2	0.0001	1	0.0001	242.56	<0.0001	
	A^3	0.0000	1	0.0000	41.19	0.0001	
	Residual	2.391×10^{-6}	9	2.657×10^7			
	Lack of Fit	2.391×10^{-6}	1	2.391×10^6			
	Pure Error	0.0000	8	0.0000			
	Cor Total	7.72	12				

Table 13. Results of the ANOVA for the Variable Response ESE.

Response	Source	Sum of Squares	Df	Mean Square	F-Value	p-Value > F	Significance
ESE	Model	0.0006	3	0.0002	148.03	<0.0001	significant
	A-JF	0.0002	1	0.0002	124.31	<0.0001	
	A^2	0.0002	1	0.0002	123.06	< 0.0001	
	A^3	0.0000	1	0.0000	27.93	0.0005	
	Residual	0.0000	9	1.343×10^6			
	Lack of Fit	0.0000	1	0.0000			
	Pure Error	0.0000	8	0.0000			
	Cor Total	0.0006	12				

The statistical technique known as the coefficient of determination (R^2) can be used to evaluate the accuracy and dependability of a predictive model [58,59]. The R^2 coefficient serves as a measure of the extent to which the model that has been fitted conforms to the data that has been observed [67,68]. The metric evaluates the degree of congruence between the model and the data [69]. The value of R-squared quantifies the proportion of the dependent variable's variation that can be attributed to the independent variables [70]. It is customary for this numerical value to vary within the range of zero to one [71]. Typically, a higher R-squared value indicates a superior model performance. The study yielded R-square values of 0.9997, 0.9732, 0.9485, 0.9202, 0.9973, 0.999, and 0.9801 for slump, CS, STS, FS, WA, EC, and ESE, respectively, after 28 days from the casting process. The models were deemed to have an excellent fit to the data based on the high determination coefficient values. Moreover, an inconsistency of 30% between the expected and modified R-squared values is considered insufficient. The signal-to-noise ratio is contingent upon the sufficiency of the precision level, necessitating a minimum threshold of 4 [57,58]. The present study reports the values obtained for Adequate Precision, which were 291.9249, 28.5585, 21.1222, 17.1756, 90.8653, 7414.069, and 32.8631, respectively, subsequent to the 28th day of the curing process. The data presented indicate a positive trajectory, suggesting that the models could potentially serve as a guide for informing the design process.

Various parameters, including Flowability, CS test, STS test, FS, WA, EC, and ESE, were investigated in the present study. The data were collected 28 days after casting and analyzed using graphs depicting real versus anticipated values, as shown in Figures 9–15. The coherence of the models' prognostications regarding the responses can be deduced from the observation that the data points congregated in close proximity to the line that yielded the most optimal alignment. The degree of conformity between the data points and the line of best fit in plots that compare actual and predicted values serves as an indicator of the similarity between the anticipated and observed outcomes [72]. The residual graphs for each response variable reveal a consistent distribution of sample points near the regression line. This finding supports the assertion that the designs are effective. This suggests that the residual terms followed a normal distribution. To summarize, the statistical outcomes obtained for each response have been assessed as satisfactory and fell within the acceptable range.

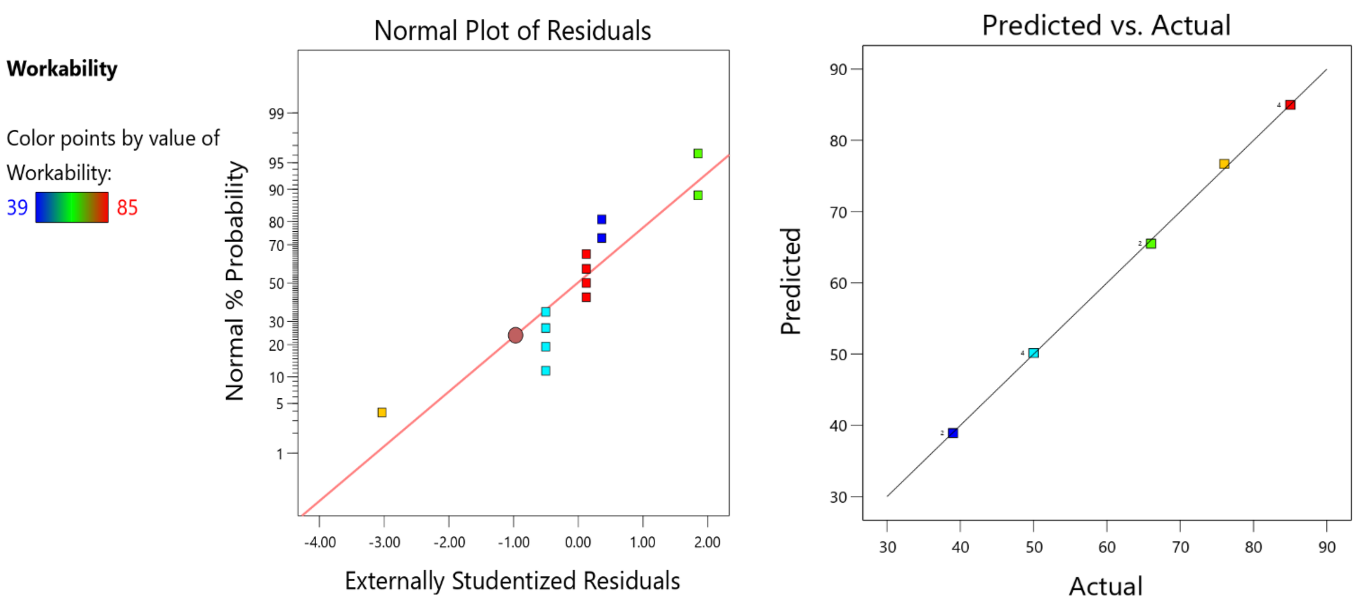

Figure 9. Normal plot of residuals (**left**) & predicted vs actual (**right**) values for Slump flow.

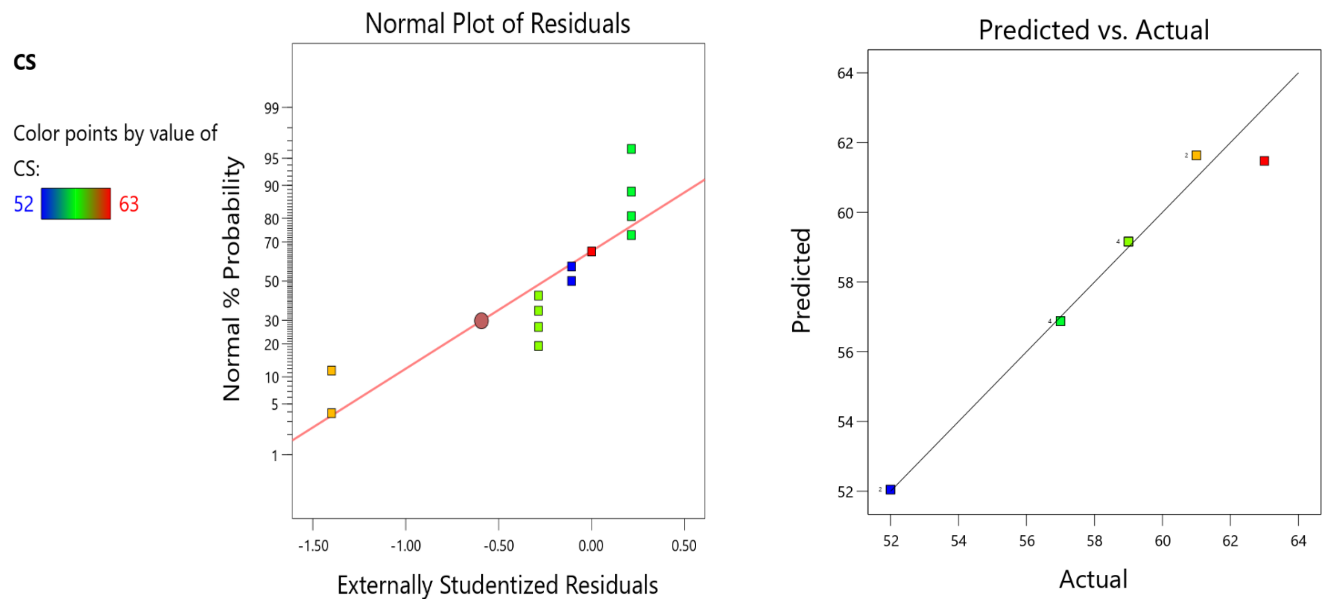

Figure 10. Normal plot of residuals (**left**) & predicted vs actual (**right**) values for CS.

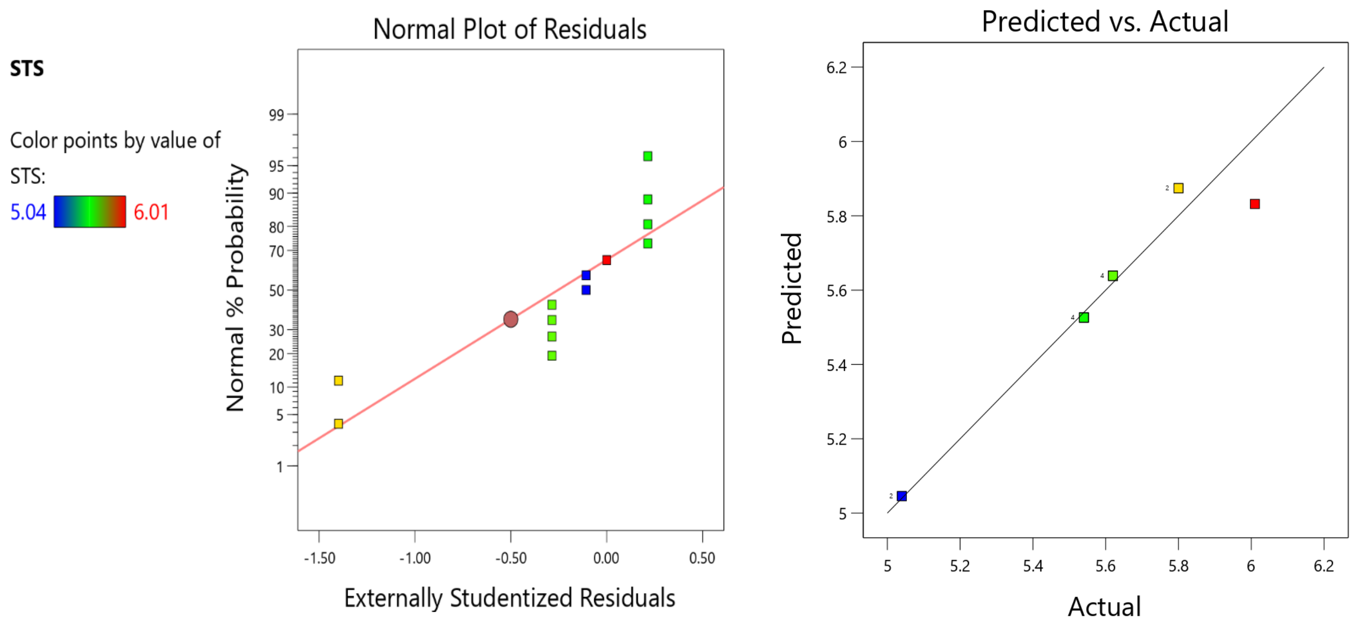

Figure 11. Normal plot of residuals (**left**) & predicted vs actual (**right**) values for STS.

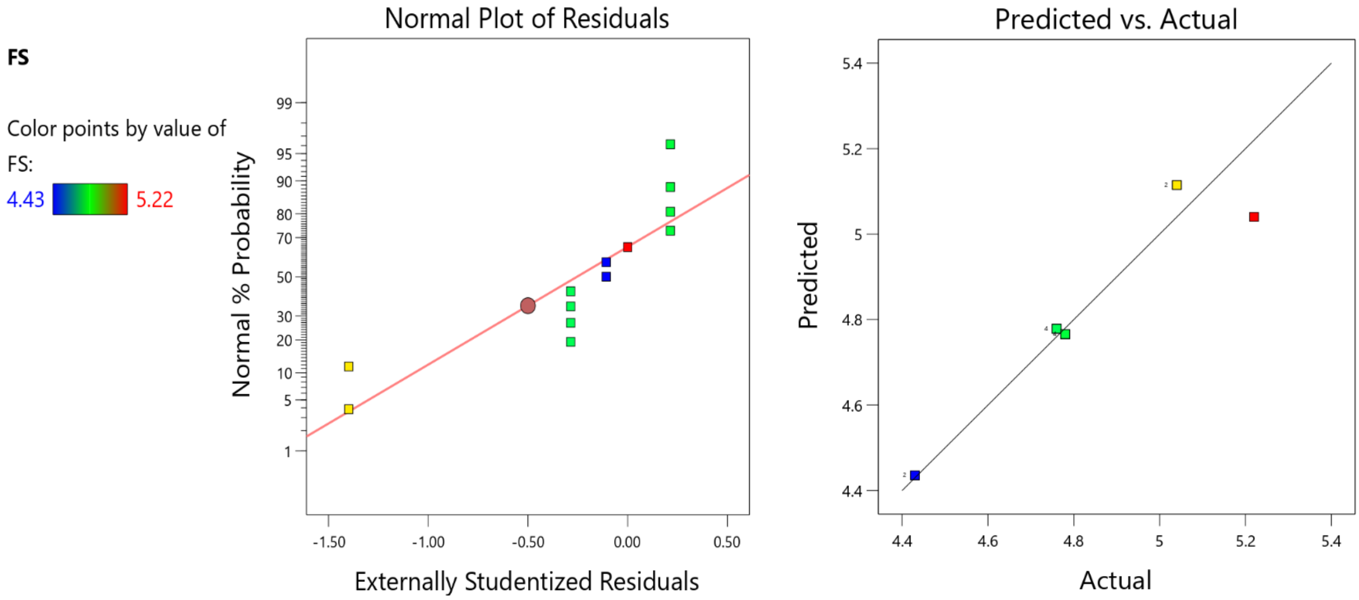

Figure 12. Normal plot of residuals (**left**) & predicted vs actual (**right**) values for FS.

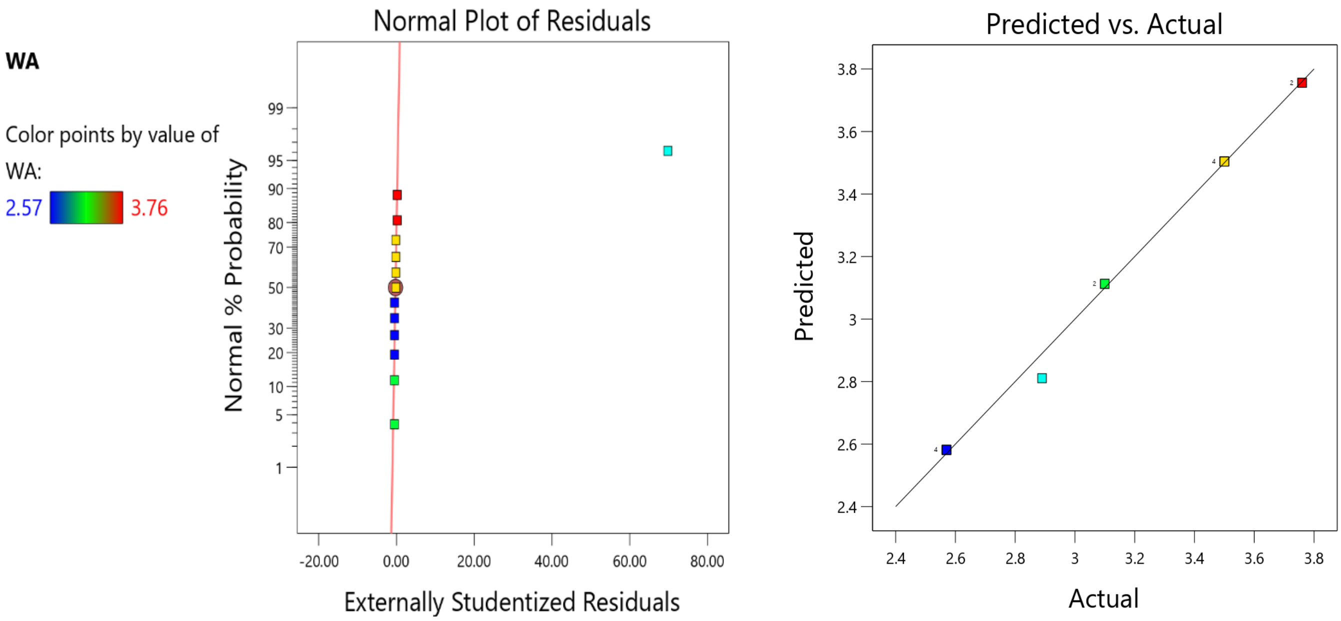

Figure 13. Normal plot of residuals (**left**) & predicted vs actual (**right**) values for WA.

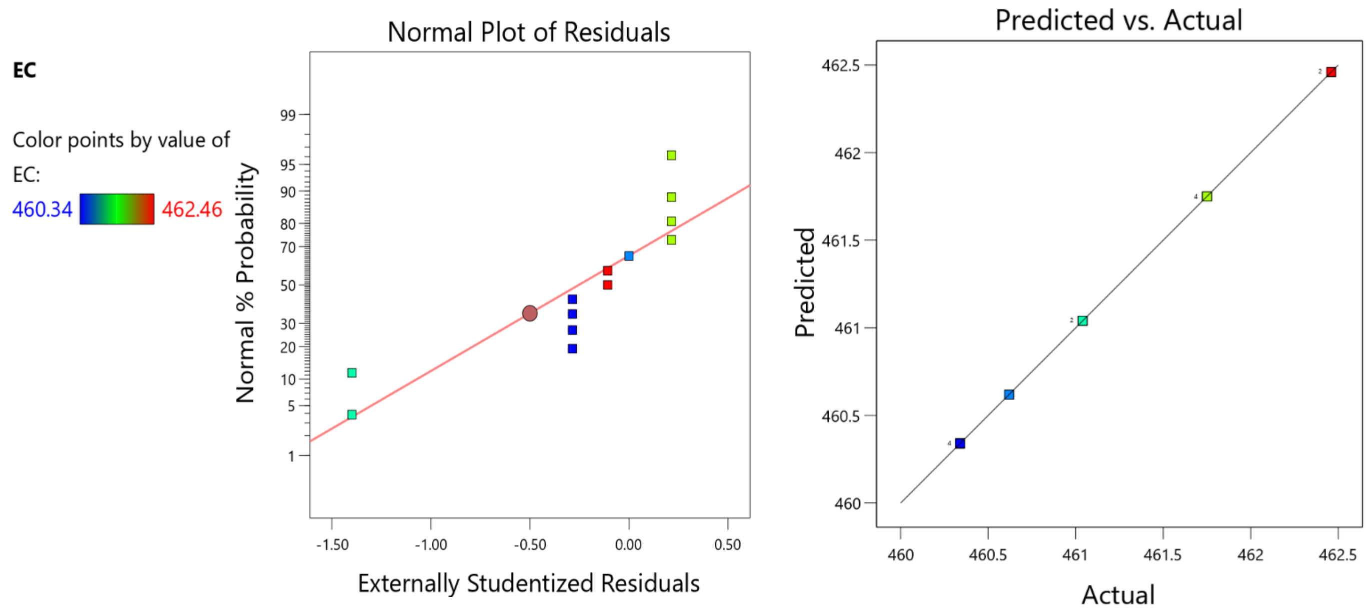

Figure 14. Normal plot of residuals (**left**) & predicted vs actual (**right**) values for EC.

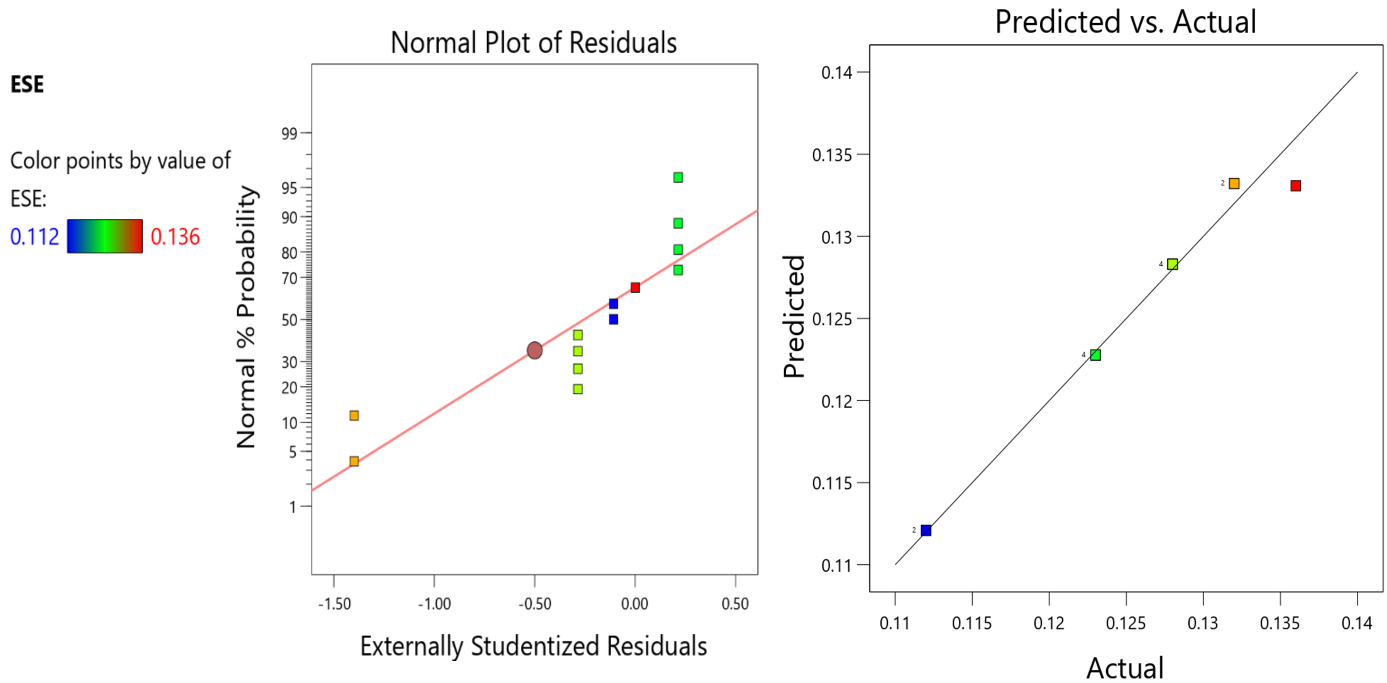

Figure 15. Normal plot of residuals (**left**) & predicted vs actual (**right**) values for ESE.

4.1. Impacts of Jute Fiber on Concrete's Fresh Properties

Slump Flow

The ANOVA results for the response variable of slump values are presented in Table 7. The quadratic approach was selected, as it delivered the most optimal fit to the data obtained from the flowability evaluation. The statistical implication of the model is demonstrated by its F-value of 18,295.35. The probability of obtaining an F-value of such magnitude solely due to chance variation is extremely low, with a probability of 0.01%. The likelihood of this event occurring is exceedingly minimal. When the *p*-values are less than 0.0500, it is feasible to infer that the model terms encompass a significant amount of value. In the given circumstance, variables A and A^2 contribute significantly to the model. Model terms with values exceeding 0.1000 are considered insignificant and are therefore excluded from consideration. Model reduction may improve a model's quality, especially if most of its terms are unnecessary outside of those needed to maintain the hierarchical structure.

$$SF = 57.3192 - 23.0267 \times A + 4.61681 \times A^2 \quad (2)$$

4.2. Impact of Jute Fiber on the Mechanical Properties of Concrete

4.2.1. Compressive Strength

Table 8. Results of the ANOVA for the Variable Response 28-day CS. presents the outcome of the ANOVA test for CS. After careful consideration, the cubic model was found to be the most applicable model for the dataset of CS. The model is statistically significant, as shown by the result of 108.90 for the F-value, which was performed earlier. The study found a 0.01% chance of a large F-value being caused by random fluctuation. If the *p*-values are less than 0.0500, the model terms are statistically significant. The model terms A, A^2, and A^3 hold significant importance in the given scenario. If the values exceed 0.1000, the inference can be made that the model parameters' influence on the outcome lacks statistical significance. The technique of model reduction can be advantageous in enhancing the overall quality of a model when a considerable proportion of model terms are deemed insignificant, with the exception of those that are necessary to maintain the hierarchy. This phenomenon occurs due to the removal of essential terms necessary for maintaining hierarchical structures. Utilizing an equation with variables that are encoded can facilitate the projection of a result for a specific level of each constituent. In many instances, a value of +1 indicates elevated levels of a component, whereas a value of −1 indicates decreased levels of the same component. The encoded equation's factor coefficients may be used to rank the components' relevance.

$$CS = 59.7146 - 7.57748 \times A - 4.11086 \times A^2 + 4.02256 \times A^3 \quad (3)$$

4.2.2. Split Tensile Strength

Table 9. Results of the ANOVA for the Variable Response STS on the 28th day presents the outcome of the ANOVA test for STS. It was determined that the cubic model offered the best possible match for the STS when applied to concrete. The statistical significance of the model can be evaluated using the Model F-value, which was computed as 55.29 in this particular case. The probability of observing an F-value in this range due to random fluctuations is vanishingly small, specifically 0.01%. A significant conclusion can be inferred regarding the threshold of statistical importance of the model's terms when the *p*-values are less than 0.05. The model terms A, A^2, and A^3 hold considerable significance in the given context. If the values exceed 0.1000, The analysis suggests that the model terms lack statistical significance in their impact on the outcome. When a considerable proportion of model terms are deemed insignificant, with the exception of those that are necessary to maintain hierarchy, the technique of model reduction can be advantageous in enhancing the overall efficacy of the model. This phenomenon occurs due to the removal of non-essential words that do not contribute to the establishment of a hierarchical structure. Variable-coded equations anticipate outcomes for different component degrees. The conventional approach involves assigning a value of +1 to signify elevated levels of constituents, while a value of −1 is allocated to indicate reduced levels. The reason for this is that a value of +1 denotes elevated tiers. By comparing factor coefficients, the encoded equation can show how much each component contributes. As a consequence, individuals are capable of ascertaining the extent to which each constituent element contributes to the entirety.

$$STS = 5.74488 - 0.550315 \times A - 0.402757 \times A^2 + 0.253897 \times A^3 \quad (4)$$

4.2.3. Flexural Strength

Table 10. Results of the ANOVA for the Variable Response FS on the 28th day presents the outcome of the ANOVA test for FS. The cubic model is chosen as the best fit model for FS. The model has a statistically significant F-value of 34.60, which may be interpreted

as a measure of how significant the model is statistically. A mere 0.01% of the possibility of finding an F-value of equal size as the only source of variability in the dataset may be attributed to the fact that this likelihood is very low. A *p*-value below the threshold of 0.0500 is indicative of the statistical significance of the model terms. The variables of utmost significance in the given scenario are A, A^2, and A^3. In cases where the model terms exhibit non-significance, values exceeding 0.1000 indicate such a phenomenon. Model reduction may improve a model's quality, especially when a large percentage of its terms are superfluous, other than those needed to preserve the hierarchical structure. The determination of the solution for given values of individual components can be predicted by employing an equation that is formulated in relation to variables represented by codes. In general, the numerical values of +1 and −1 are commonly employed to indicate elevated and reduced levels of the constituents, correspondingly. By employing a coded equation and conducting an evaluation of the factor coefficients related to each constituent, it is possible to determine the comparative effect of the constituents.

$$FS = 4.98201 - 0.567112 \times A - 0.374792 \times A^2 + 0.395643 \times A^3 \tag{5}$$

4.3. Durability

Water Absorption

Table 11. Results of the ANOVA for the Variable Response WA presents the outcome of the ANOVA test for WA. After careful analysis, it was determined that the quadratic model exhibited the highest level of accuracy in relation to the data and was subsequently selected. The model's F-value, which is 1827.77, serves as an indicator of the model's statistical significance. The probability of observing an F-value of such magnitude due to chance variation alone is considerably small, accounting for only 0.01% of the total probability. If the *p*-values are below 0.0500, it is feasible to infer that the model terms encompass a significant amount of value. The significance of both A and A^2 as model words in the current context under examination is evident. Values of a variable exceeding 0.1000 suggest a lack of statistical significance in the model terms. The implementation of model reduction can enhance the overall quality of a model by eliminating numerous model terms that are deemed insignificant, except for those that are essential for maintaining hierarchies. Using a pre-established equation with coded variables, one can make an educated estimate of the solution for each component based on the provided values. Typically, the numerical values +1 and −1 are used to represent increased and decreased levels of constituents, respectively. These values could alternatively be characterized as "heightened" and "reduced." The encoded equation can be utilized to ascertain the comparative impact of the constituents. The goal can be achieved by comparing and contrasting the coefficients of factors associated with each element.

$$WA = 3.32575 + 0.587063 \times A - 0.157063 \times A^2 \tag{6}$$

4.4. Impact of Jute Fiber on Sustainability

4.4.1. Embodied Carbon

Table 12. Results of the ANOVA for the Variable Response EC presents the outcome of the ANOVA test for EC. The cubic model was determined to be the model that provided the best overall match. The statistical relevance of the model is demonstrated by its F-value of 9,684,954.96, which can be found within the model. Random fluctuation has a 0.01% chance of discovering an F-value of such magnitude. Statistically significant model terms have *p*-values less than 0.0500. The model terms that hold significance in this instance are A, A^2, and A^3. Model terms are considered insignificant if their values exceed 0.1000. In the event that a considerable number of model terms are deemed insignificant, excluding those that are necessary to maintain hierarchy, the process of model reduction may enhance the overall quality of the model. The utilization of a coded factor equation enables the generation of anticipations concerning the reaction. The accuracy of these predictions is contingent

upon specific quantities of individual constituents. The aforementioned levels can be inferred from the encoded components. The upper and lower limits of the constituents are assigned default values of +1 and −1, respectively. The previously mentioned values are applied to both the upper and lower limits of the components. Through a comparison of the factor coefficients assigned to each element, the encoded equation can be utilized as a valuable tool for conducting a comparative assessment of the respective significance of the diverse components.

$$EC = 461.395 + 1.06455 \times A + 0.00547733 \times A^2 - 0.00459421 \times A^3 \quad (7)$$

4.4.2. Eco-Strength Efficiency

Table 13. Results of the ANOVA for the Variable Response presents the outcome of the ANOVA test for ESE. The cubic model was identified as the ideal model that exhibited the highest degree of overall conformity. The statistical significance of the model can be inferred from the F statistic value of 148.03. The probability of observing an F-value of this magnitude due to chance alone is exceedingly low, with a likelihood of 0.01%. A model term is significant if its p-value is less than 0.0500. The significance of model terms A, A^2, and A^3 in this context stems from their pertinence to the given scenario. If the values exceed 0.1000, it can be inferred that the model terms are not statistically substantial in influencing the outcome. If a significant proportion of model terms are deemed irrelevant, with the exception of those necessary for maintaining hierarchy, engaging in model reduction could be a beneficial approach for improving the model. The reason for this is that the implementation of model reduction techniques has the potential to enhance the model's performance. By taking into consideration a specified amount of each encoded element, the equation may anticipate a reaction's result. Typically, the convention is to designate a numerical value of 1 to the uppermost tier of a categorical variable, while the tier with the least value is commonly assigned a numerical value of −1.

$$ESE = 0.128968 - 0.0166097 \times A - 0.00876944 \times A^2 + 0.00850453 \times A^3 \quad (8)$$

5. Optimization and Validation of Model

The simultaneous evaluation of multiple responses can cause difficulty in achieving the optimal value. Consequently, numerous responses are optimized through the utilization of multi-objective optimization methodologies. The present investigation employed a compromise optimization approach for eight multiple responses. As previously mentioned, a singular factor was utilized in the form of the quantity of Jute fiber (JF). The study employed eight responses as the dependent variable, namely Slump (mm), STS test, FS, WA test, EC, and ESE. The Response Surface Methodology (RSM) was employed to determine the optimal factor composition, comprising eight distinct attributes. The study utilized Design Expert software version 13 to optimize the process of design. Every variable and answer has a predetermined level of significance. Table 14 illustrates that the utilization of a multi-objective optimization approach results in a solution that closely approximates and satisfies the predetermined upper and lower constraints. The assessment of appeal is contingent upon the level of resemblance between the suggested resolution and the factual outcome. In order to optimize outcomes, it is recommended to maintain a desirability score in close proximity to unity. The desirability value of 0.994 suggests that it is feasible to optimize the response. The study identified the top eight response values for various properties of the material, including slump, CS, STS, absorption of water, FS, EC, and ESE. A desirability value of 0.809 was ascertained for these values. The corresponding values for each property were 39, 52.073, 5.049, 4.436, 3.753, 462.45, and 0.1121, respectively (See Figures 16 and 17).

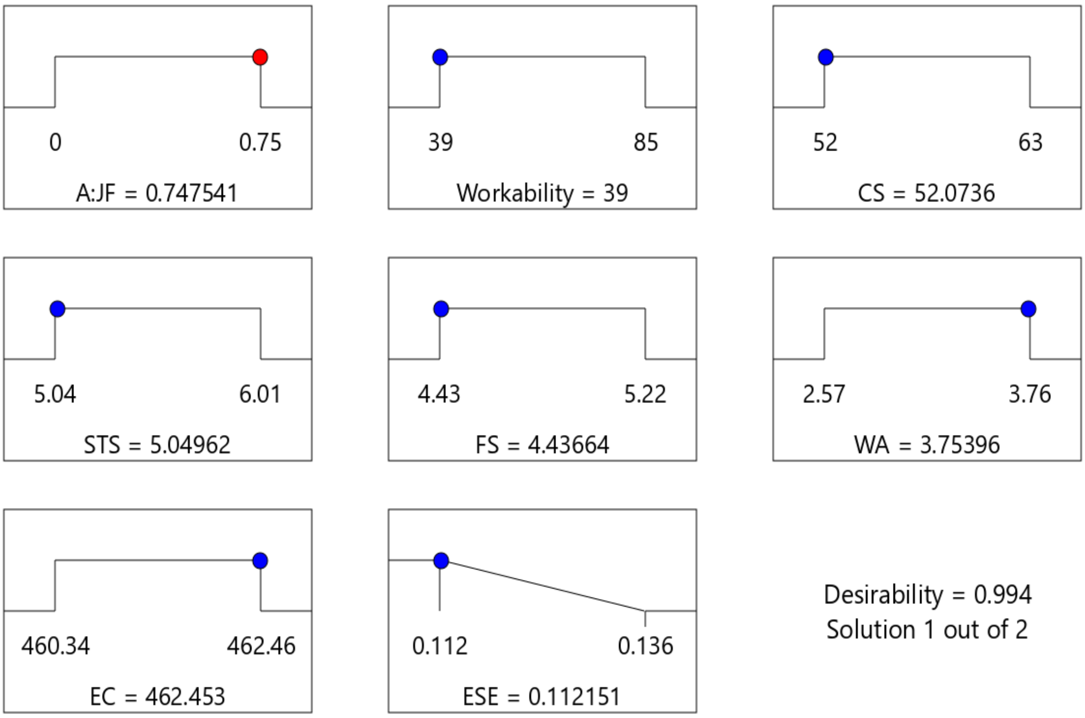

Figure 16. Ramp Diagram for optimization of all responses.

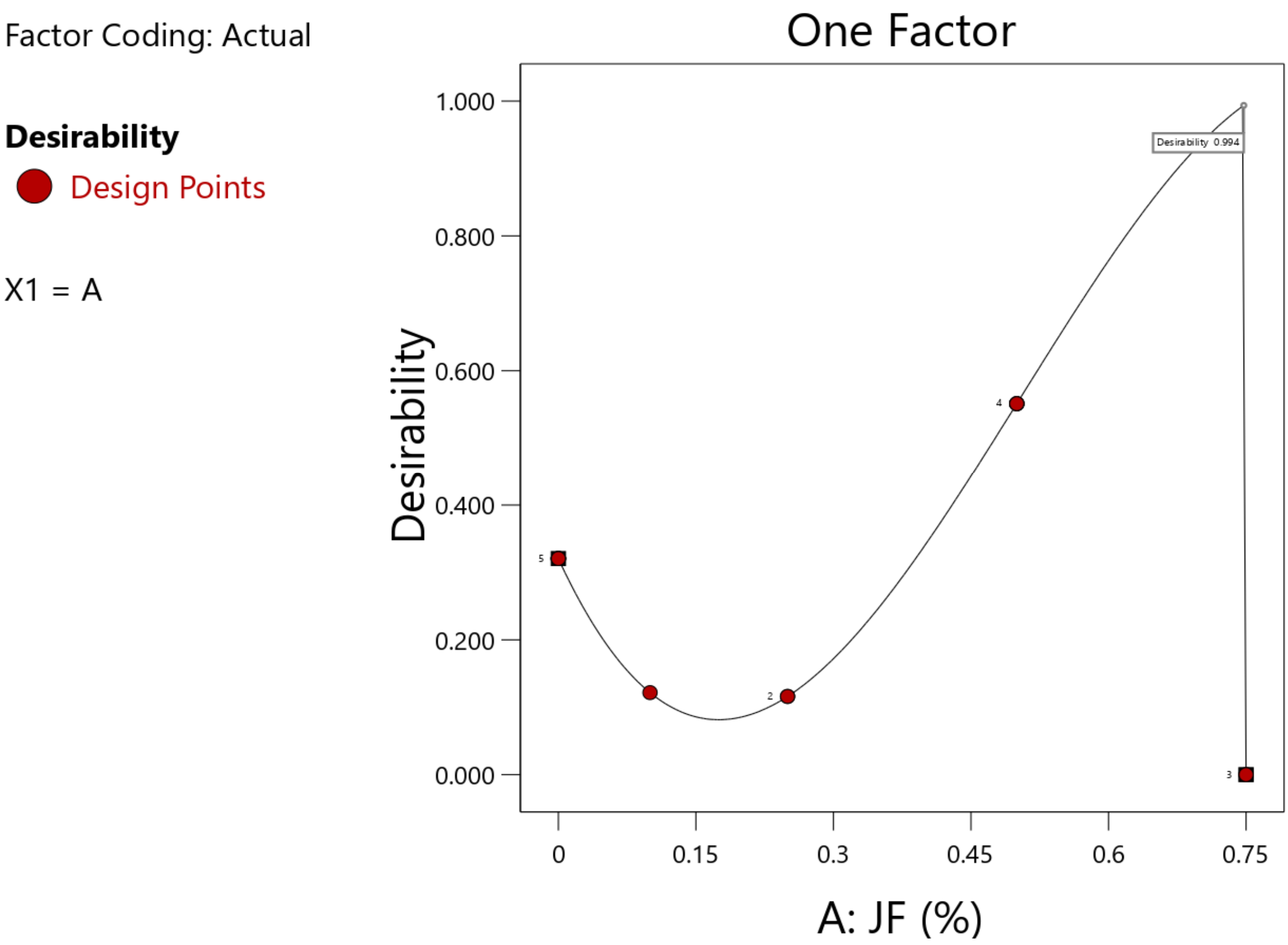

Figure 17. One factor diagram for desirability for optimization of concrete blended with JF.

Table 14. Optimization of each response.

Factors		Variable (Input Factors)	Response (Output Factors)						
		Carbon Fiber	Slump	CS	STS	Flexural Strength	WA	EC	ESE
Value	Minimum	0%	85	59	5.626	4.76	2.57	460.34	0.128
	Maximum	0.75%	39	52	5.047	4.43	3.76	462.462	0.112
Goal			In range	In range	In range	In range	In range	In range	Minimize
Optimization results		0.747%	39	52.073	5.049	4.436	3.753	462.45	0.1121
Desirability		0.994							

The disparities between the experimental and anticipated values obtained through response optimization are presented in Table 15. Validation. The samples were cast using optimal techniques, and to discriminate between anticipated and observed values, the inaccuracy is expressed as a percentage. It is evident that the mean error rate for all the responses is below 5%. This illustrates a high degree of accuracy in the model.

Table 15. Validation.

Responses	Predicted	Experimental	Error (%)
Slump	39	40	2.56
CS	52.073	53.7	3.12
STS	5.049	5.2	2.99
FS	4.436	4.59	3.47
WA	3.753	3.9	3.91

6. Conclusions

The present investigation involved the production of concrete utilizing jute fiber as a constituent material. This study aimed to determine the impact of jute fiber on the fresh, mechanical, and environmental properties of concrete. By employing computational aspects and statistical models, the Response Surface Methodology (RSM) was employed to estimate the desired properties of concrete through the identification of the optimal amount of its primary component. The present investigation utilized analysis of variance (ANOVA) to examine the impact of jute fiber on the outcomes. The present inquiry has yielded a catalogue of the most noteworthy discoveries.

- The empirical evidence suggests that the optimal and preferred results for concrete mixed with JF are achieved when the concrete contains 0.10% JF. Concrete's fresh and hardened features do not exhibit any favorable effects when the amount of JF exceeds 0.10%. The outcomes of this study specify that the implementation of forecast models that rely on the *p*-value can produce statistically significant results and contribute significantly to the evaluation of the mechanical properties of fresh and hardened carbon fiber-reinforced concrete. The numerical results for each response were deemed acceptable and consistent with the anticipated range.
- The coefficients of determination (R-squared) for slump flow, CS of concrete, STS, WA, EC, and ESE are 0.9997, 0.9732, 0.9485, 0.9202, 0.9973, 0.999, and 0.9801, correspondingly.
- The investigation demonstrated that the optimal slump was detected when the JF percentage was 0%, while the minimum slump flow was recorded at a JF percentage of 0.75%. The observed decrease in the slump flow of fresh concrete has been linked to the presence of JF accumulations within the concrete.

- The incorporation of 0.10% JF in concrete resulted in the attainment of the maximum CS, STS, and FS, measuring 63 MPa, 6.01 MPa, and 5.22 MPa, respectively.
- The investigation produced optimized outcomes for diverse parameters, encompassing slump, CS of concrete, STS, WA, EC, and ESE. The aforementioned parameters were determined to have values of 39, 52.073, 5.049, 4.436, 3.753, 462.45, and 0.1121, respectively. The level of desirability associated with these responses was found to be 0.994.
- The equations obtained can be utilized to predict the concrete's properties by adding different percentages of JF.

Author Contributions: Conceptualization, M.B.K., A.W. and D.R.; methodology, M.B.K. and A.W.; software, N.S. and H.A.; validation, D.R., O.B. and C.C.; formal analysis, M.B.K. and D.R.; investigation, M.B.K. and A.W.; resources, N.S.; data curation, D.R.; writing—original draft preparation, D.R. and A.W., O.B; writing—review and editing, D.R., N.S., A.W. and H.A.; visualization, M.B.K.; supervision, N.S., M.I. and H.A.; project administration, D.R. and C.C.; funding acquisition N.S. All authors have read and agreed to the published version of the manuscript.

Funding: This study is supported via funding from Prince Sattam bin Abdulaziz University project number (PSAU/2023/R/1444).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data related to this research are not available for public access.

Acknowledgments: Authors want to thank Rj Intan Shafinaz (lab attendant at Civil Engineering Department) in Universiti Tecknologi Petronas for helping in conducting the experiments.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

JF	Jute fiber
CS	Compressive strength
STS	Split tensile strength
FS	Flexural strength
WA	Water absorption
EC	Embodied carbon
ESE	Eco-strength efficiency
NFRC	Natural fiber reinforced concrete

References

1. Waqar, A.; Shafiq, N.; Khan, M.B.; Mansoor, M.S. A Systematic Literature Review on Risk Analysis of Health and Safety in Oil Refinery and Onshore Pipeline Construction Projects. In Proceedings of the 2022 International Conference on Data Analytics for Business and Industry (ICDABI), Sakhir, Bahrain, 25–26 October 2022. [CrossRef]
2. Gagg, C.R. Cement and concrete as an engineering material: An historic appraisal and case study analysis. *Eng. Fail. Anal.* **2014**, *40*, 114–140. [CrossRef]
3. Karim, M.; Abdullah, M.; Deifalla, A.; Azab, M.; Waqar, A. An assessment of the processing parameters and application of fibre-reinforced polymers (FRPs) in the petroleum and natural gas industries: A review. *Results Eng.* **2023**, *18*, 101091. [CrossRef]
4. Sor, N.H.; Ali, T.K.M.; Vali, K.S.; Ahmed, H.U.; Faraj, R.H.; Bheel, N.; Mosavi, A. The behavior of sustainable self-compacting concrete reinforced with low-density waste Polyethylene fiber. *Mater. Res. Express* **2022**, *9*, 035501. [CrossRef]
5. Kennedy, C.; Bheel, N.; Nadeem, G.; Benjeddou, O.; Waqar, A. Efficiency of ficus sycomorus exudates as corrosion inhibitor for mild steel pipes in acid concentrated water and soil. *Saf. Extreme Environ.* **2023**, *5*, 1–10. [CrossRef]
6. Castro-Gomes, J.P.; Pereira de Oliveira, L.A.; Pereira, C.G. Discussion of Aggregate and Concrete Water Absorption and Permeability Testing Methodology. 2003, pp. 185–202. Available online: https://www.researchgate.net/publication/235323702_Discussion_of_Aggregate_and_Concrete_Water_Absorption_and_Permeability_Testing_Methodology (accessed on 27 June 2023).
7. Versus, M.; Fibers, M. Fiber Reinforced Concrete (FRC) Tip Sheet. 2019, pp. 1–3. Available online: https://ftp.dot.state.tx.us/pub/txdot/mtd/ta/frc-tip-sheet.pdf (accessed on 27 June 2023).
8. Beckman, I.P.; Lozano, C.; Freeman, E.; Riveros, G. Fiber Selection for Reinforced Additive Manufacturing. *Polymers* **2021**, *13*, 2231. [CrossRef]
9. Karim, M.; Abdullah, M.; Ahmed, T. An Overview: The Processing Methods of Fiber-reinforced Polymers (FRPs). *J. Mech. Eng. Technol.* **2021**, *12*, 10–24. [CrossRef]

10. Rocha, D.L.; Júnior, L.U.D.T.; Marvila, M.T.; Pereira, E.C.; Souza, D.; de Azevedo, A.R.G. A Review of the Use of Natural Fibers in Cement Composites: Concepts, Applications and Brazilian History. *Polymers* **2022**, *14*, 2043. [CrossRef] [PubMed]
11. Alojaly, H.M.; Hammouda, A.; Benyounis, K.Y. *Recent Developments in Metal Matrix Composites with Fiber Reinforcement*; Elsevier: Amsterdam, The Netherlands, 2022.
12. Holschemacher, K.; Juknat, M.; Höer, S. Non-metallic fibres for structural concrete. In Proceedings of the International Conference "Modern Concrete and Reinforced Concrete", Minsk, Belorussia, 16–19 October 2007.
13. Guignone, G.; Calmon, J.L.; Vieira, G.; Zulcão, R.; Rebello, T.A. Life Cycle Assessment of Waste Glass Powder Incorporation on Concrete: A Bridge Retrofit Study Case. *Appl. Sci.* **2022**, *12*, 3353. [CrossRef]
14. Vairagade, V.S.; Kene, K.S. Strength of Normal Concrete Using Metallic and Synthetic Fibers. *Procedia Eng.* **2013**, *51*, 132–140. [CrossRef]
15. Mohammed, H.; Shakeel, N. The effect of metallic and non-metallic fiber on the mechanical properties of waste ceramic concrete. *Innov. Infrastruct. Solut.* **2021**, *6*, 1–15.
16. Ahmad, J.; Arbili, M.M.; Majdi, A.; Althoey, F.; Deifalla, A.F. Performance of concrete reinforced with jute fibers (natural fibers): A review. *J. Eng. Fibers Fabr.* **2022**, *17*, 15589250221121871. [CrossRef]
17. Khan, M.B.; Shafiq, N.; Waqar, A.; Imran, M. Production of Biochar from Waste Biomass Feedstock and its Applications in Sustainable Construction. *Xi'an Shiyou Xueyuan Xuebao/J. Xi'an Pet. Inst. (Nat. Sci. Ed.)* **2023**, *19*, 662–690.
18. Gowda, Y.; Girijappa, T.; Rangappa, S.M. Natural Fibers as Sustainable and Renewable Resource for Development of Eco-Friendly Composites: A Comprehensive Review. *Front. Mater.* **2019**, *6*, 226. [CrossRef]
19. Waqar, A.; Othman, I.; Shafiq, N.; Mansoor, M. Applications of AI in oil and gas projects towards sustainable development: A systematic literature review. *Artif. Intell. Rev.* **2023**, *56*, 1–28. [CrossRef]
20. Begum, K.; Islam, M.A. Natural fiber as a substitute to synthetic fiber in polymer composites: A review. *Res. J. Eng. Sci.* **2013**, *2*, 46–53.
21. Mahir, F.; Keya, K.N.; Sarker, B.; Nahiun, K.; Khan, R. A brief review on natural fiber used as a replacement of synthetic fiber in polymer composites. *Mater. Eng. Res.* **2019**, *1*, 88–99. [CrossRef]
22. Hussien, N.T.; Oan, A.F. The use of sugarcane wastes in concrete. *J. Eng. Appl. Sci.* **2022**, *69*, 31. [CrossRef]
23. Balasubramani, V.; Kumar, R.S. Natural Fibers in Concrete—A Review Natural Fibers in Concrete—A Review. *IOP Conf. Series Mater. Sci. Eng.* **2021**, *1055*, 012038. [CrossRef]
24. Prakash, R.; Raman, S.N.; Divyah, N.; Subramanian, C.; Vijayaprabha, C.; Praveenkumar, S. Fresh and mechanical characteristics of roselle fibre reinforced self-compacting concrete incorporating fly ash and metakaolin. *Constr. Build. Mater.* **2021**, *290*, 123209. [CrossRef]
25. Athijayamani, A.; Thiruchitrambalam, M.; Vairavan, M.; Pazhanivel, B. Mechanical properties of natural fibers reinforced polyester hybrid composite. *Int. J. Plast. Technol.* **2010**, *14*, 104–116. [CrossRef]
26. Mitschang, P.; Christmann, M. 8—Continuous fiber reinforced profiles in polymer matrix composites. In *Woodhead Publishing Series in Composites Science and Engineering*; Advani, S.G., Hsiao, K.-T., Eds.; Woodhead Publishing: Sawston, UK, 2012; pp. 209–242.
27. Juarez, C.A.; Fajardo, G.; Monroy, S.; Duran-Herrera, A.; Valdez, P.; Magniont, C. Comparative study between natural and PVA fibers to reduce plastic shrinkage cracking in cement-based composite. *Constr. Build. Mater.* **2015**, *91*, 164–170. [CrossRef]
28. Zakaria, M.; Ahmed, M.; Hoque, M.; Islam, S. Scope of using jute fiber for the reinforcement of concrete material. *Text. Cloth. Sustain.* **2016**, *2*, 123. [CrossRef]
29. Wang, X.; Chang, L.; Shi, X.; Wang, L. Effect of Hot-Alkali Treatment on the Structure Composition of Jute Fabrics and Mechanical Properties of Laminated Composites. *Materials* **2019**, *12*, 1386. [CrossRef]
30. Song, X.; Zhang, Y.; Zou, T.; Li, Y.; Wang, P.; Hu, D. The reinforcement and toughening of jute/PLA (lactic acid) composite material with modified-rubber/SiO2 core-shell particles. *Mater. Today Sustain.* **2022**, *19*, 100198. [CrossRef]
31. Naik, N.; Shivamurthy, B.; Thimappa, B.H.S.; Govil, A.; Gupta, P.; Patra, R. Enhancing the mechanical properties of jute fiber reinforced green composites varying cashew nut shell liquid composition and using mercerizing process. *Mater. Today Proc.* **2019**, *19*, 434–439. [CrossRef]
32. Islam, M.S.; Ahmed, S.J. Influence of jute fiber on concrete properties. *Constr. Build. Mater.* **2018**, *189*, 768–776. [CrossRef]
33. Serpieri, R.; Monaco, M. A percolation-threshold model for evaluating permeability in Portland pastes with high water-cement ratio. *J. Build. Eng.* **2023**, *70*, 106328. [CrossRef]
34. Bowden, G.D.; Pichler, B.J.; Maurer, A. A Design of Experiments (DoE) Approach Accelerates the Optimization of Copper-Mediated 18F-Fluorination Reactions of Arylstannanes. *Sci. Rep.* **2019**, *9*, 1–10. [CrossRef]
35. Zahraee, S.; Rezaei, G.; Memari, A.; Afshar, J.; Rohani, J.M. Teaching Design of Experiment and Response Surface Methodology Using Paper Helicopter Experiment. In Proceedings of the 4th International Graduate conference on Engineering, Science and Humanity, Johor Bahru, Malaysia, 16–17 April 2013.
36. Khan, M.B.; Waqar, A.; Bheel, N.; Shafiq, N.; Sor, N.H. Optimization of fresh and mechanical characteristics of carbon fiber-reinforced concrete composites using response surface technique. *Buildings* **2023**, *13*, 852. [CrossRef]
37. Dejaegher, B.; Heyden, Y.V. Experimental designs and their recent advances in set-up, data interpretation, and analytical applications. *J. Pharm. Biomed. Anal.* **2011**, *56*, 141–158. [CrossRef]

38. Ing, D.S.; Li, X.; Chong, B.W.; Othman, R.; Jaya, R.P. Properties of Concrete with Eggshell Powder: A Review. *Phys. Chem. Earth Parts A/B/C* **2020**, *120*, 102951. [CrossRef]
39. Wu, S.S.; Li, B.Z.; Yang, J.G.; Shukla, S.K. Predictive modeling of high-performance concrete with regression analysis. In Proceedings of the 2010 IEEE International Conference on Industrial Engineering and Engineering Management, Macao, China, 7–10 December 2010; pp. 1009–1013. [CrossRef]
40. Tanco, M.; Viles, E.; Ilzarbe, L.; Alvarez, M.J. Is design of experiments really used? A survey of Basque industries. *J. Eng. Des.* **2008**, *19*, 447–460. [CrossRef]
41. Silva, F.A.N.; Delgado, J.M.P.Q.; Cavalcanti, R.S.; Azevedo, A.C.; Guimarães, A.S.; Lima, A.G.B. Use of Nondestructive Testing of Ultrasound and Artificial Neural Networks to Estimate Compressive Strength of Concrete. *Buildings* **2021**, *11*, 44. [CrossRef]
42. Poorarbabi, A.; Ghasemi, M.; Moghaddam, M.A. Concrete compressive strength prediction using non-destructive tests through response surface methodology. *Ain Shams Eng. J.* **2020**, *11*, 939–949. [CrossRef]
43. Cibilakshmi, G.; Jegan, J. A DOE approach to optimize the strength properties of concrete incorporated with different ratios of PVA fibre and nano-Fe_2O_3. *Adv. Compos. Lett.* **2020**, *29*, 2633366X2091388. [CrossRef]
44. Chong, B.W.; Othman, R.; Sheng, T.; Jaya, R.P.; Abdullah, M.M.A.B. Properties of Mortar with Waste Tyre Rubber as Partial Sand Replacement. *Key Eng. Mater.* **2021**, *879*, 49–61. [CrossRef]
45. Rizalman, A.N.; Lee, C.C. Comparison of Artificial Neural Network (ANN) and Response Surface Methodology (RSM) in Predicting the Compressive Strength of POFA Concrete. *Appl. Model. Simul.* **2020**, *4*, 210–216.
46. Lokuge, W.; Wilson, A.; Gunasekara, C.; Law, D.W.; Setunge, S. Design of fly ash geopolymer concrete mix proportions using Multivariate Adaptive Regression Spline model. *Constr. Build. Mater.* **2018**, *166*, 472–481. [CrossRef]
47. Shahidan, S.; Aminuddin, E.; Noor, K.M.; Hannan, N.I.R.R.; Bahari, N.A.S. Potential of Hollow Glass Microsphere as Cement Replacement for Lightweight Foam Concrete on Thermal Insulation Performance. *MATEC Web Conf.* **2017**, *103*, 1014. [CrossRef]
48. Alam, M.M.; Maniruzzaman, M.; Morshed, M.M. *7.10—Application and Advances in Microprocessing of Natural Fiber (Jute)–Based Composites*; Hashmi, S., Batalha, G.F., Van Tyne, C.J., Yilbas, B.B.T.-C.M.P., Eds.; Elsevier: Oxford, UK, 2014; pp. 243–260.
49. American Concrete Institute. *Building Code Requirements for Structural Concrete (ACI 318-14)*; American Concrete Institute: Farmington Hills, MI, USA, 2014.
50. ASTM. Form and Style for ASTM Standards. In *ASTM Regul.*; ASTM: West Conshohocken, PA, USA, 2009; pp. 1–97.
51. Department of Transportation. *Method of Test for Relative Mortar Strength of Portland Cement Concrete Sand*; no. 50; Department of Transportation, Division of Engineering, Transportation Laboratory: Sacramento, CA, USA, 2013; pp. 1–5.
52. Hasan, R.; Sobuz, H.R.; Akid, A.S.M.; Awall, R.; Houda, M.; Saha, A.; Meraz, M.; Islam, S.; Sutan, N.M. Eco-friendly self-consolidating concrete production with reinforcing jute fiber. *J. Build. Eng.* **2023**, *63*, 105519. [CrossRef]
53. Elgawish, M.H.; Zakaria, M.A. The effectiveness of intensive versus standard physical therapy for motor progress in children with spastic cerebral palsy. *Egypt. Rheumatol. Rehabil.* **2015**, *42*, 1–6. [CrossRef]
54. Zhang, T.; Yin, Y.; Gong, Y.; Wang, L. Mechanical properties of jute fiber-reinforced high-strength concrete. *Struct. Concr.* **2020**, *21*, 703–712. [CrossRef]
55. Song, H.; Liu, J.; He, K.; Ahmad, W. A comprehensive overview of jute fiber reinforced cementitious composites. *Case Stud. Constr. Mater.* **2021**, *15*, e00724. [CrossRef]
56. Alomayri, T.; Ali, B.; Raza, S.S.; El Hachem, C.; Ahmed, H.; Azab, M. Effect of binder strengthening using micro-silica on mechanical and absorption characteristics of HPC reinforced with reclaimed jute fibres. *Case Stud. Constr. Mater.* **2023**, *18*, e02085. [CrossRef]
57. Cushman, B.R. Energy Consumption Energy Type Nutrition Research. 2017, pp. 1–12. Available online: http://www.dartmouth.edu/~cushman/books/Numbers/Chap1-Materials.pdf (accessed on 27 June 2023).
58. Turner, L.K.; Collins, F.G. Carbon dioxide equivalent (CO_2-e) emissions: A comparison between geopolymer and OPC cement concrete. *Constr. Build. Mater.* **2013**, *43*, 125–130. [CrossRef]
59. Jones, R.; Mccarthy, M.; Newlands, M. Fly Ash Route to Low Embodied CO_2 and Implications for Concrete Construction. In Proceedings of the World of Coal Ash (WOCA) Conference, Denver, CO, USA, 9–12 May 2011.
60. Collins, F. Inclusion of carbonation during the life cycle of built and recycled concrete: Influence on their carbon footprint. *Int. J. Life Cycle Assess.* **2010**, *15*, 549–556. [CrossRef]
61. Thilakarathna, P.S.M.; Seo, S.; Baduge, K.S.K.; Lee, H.; Mendis, P.; Foliente, G. Embodied carbon analysis and benchmarking emissions of high and ultra-high strength concrete using machine learning algorithms. *J. Clean. Prod.* **2020**, *262*, 121281. [CrossRef]
62. Singh, A.K.; Mukesh, K.; Mitra, S. Carbon footprint and energy use in jute and allied fibre production. *Indian J. Agric. Sci.* **2018**, *88*, 1305–1316. [CrossRef]
63. Waqar, A.; Bheel, N.; Shafiq, N.; Othman, I.; Khan, M.B.; Mansoor, M.S.; Benjeddou, O.; Yaseen, G. Effect of volcanic pumice powder ash on the properties of cement concrete using response surface methodology. *J. Build. Pathol. Rehabil.* **2023**, *8*, 17. [CrossRef]
64. Khodaii, A.; Mousavi, E.; Khedmati, M.; Iranitalab, A. Identification of dominant parameters for stripping potential in warm mix asphalt using response surface methodology. *Mater. Struct.* **2015**, *49*, 2425–2437. [CrossRef]
65. Nassar, A.; Thom, N.; Parry, T. Optimizing the mix design of cold bitumen emulsion mixtures using response surface methodology. *Constr. Build. Mater.* **2016**, *104*, 216–229. [CrossRef]

66. Waqar, A.; Khan, M.B.; Shafiq, N.; Skrzypkowski, K. Assessment of Challenges to the Adoption of IOT for the Safety Management of Small Construction Projects in Malaysia: Structural Equation Modeling applied sciences Assessment of Challenges to the Adoption of IOT for the Safety Management of Small Constru. *Appl. Sci.* **2023**, *13*, 3340. [CrossRef]
67. Waqar, A.; Othman, I.; Shafiq, N.; Mansoor, M. Evaluating the critical safety factors causing accidents in downstream oil and gas construction projects in Malaysia. *Ain Shams Eng. J.* **2023**, 102300. [CrossRef]
68. Waqar, A.; Almujibah, H. Factors Influencing Adoption of Digital Twin Advanced Technologies for Smart City Development: Evidence from Malaysia. *Buildings* **2023**, *13*, 775. [CrossRef]
69. Waqar, A.; Othman, I.; Pomares, J. Impact of 3D Printing on the Overall Project Success of Residential Construction Projects Using Structural Equation Modelling. *Int. J. Environ. Res. Public Health* **2023**, *20*, 3800. [CrossRef] [PubMed]
70. Waqar, A.; Skrzypkowski, K.; Almujibah, H.; Zagórski, K.; Khan, M.B. Success of Implementing Cloud Computing for Smart Development in Small Success of Implementing Cloud Computing for Smart Development in Small Construction Projects. *Appl. Sci.* **2023**, *13*, 5713. [CrossRef]
71. Waqar, A.; Bheel, N.; Almujibah, H.R.; Benjeddou, O.; Alwetaishi, M.; Ahmad, M.; Sabri, M.M.S. Effect of Coir Fibre Ash (CFA) on the strengths, modulus of elasticity and embodied carbon of concrete using response surface methodology (RSM) and optimization. *Results Eng.* **2023**, *17*, 100883. [CrossRef]
72. Abdulkadir, B.; Mohammed, I. Rsm Analysis and Study on the 6 Months Compressive Strength Development and Shrinkage Behaviour of High Volume Fly Ash Rubberized ECC (HVFA-RECC). *Int. J. Adv. Res. Eng. Technol.* **2020**, *11*, 965–980. [CrossRef]