

## Article

# Workability, Strength, Modulus of Elasticity, and Permeability Feature of Wheat Straw Ash-Incorporated Hydraulic Cement Concrete

Herda Yati Binti Katman <sup>1,\*</sup>, Wong Jee Khai <sup>1</sup>, Naraindas Bheel <sup>2</sup>, Mehmet Serkan Kırgız <sup>3,4,\*</sup>,  
Aneel Kumar <sup>5</sup>, Jamal Khatib <sup>6</sup> and Omrane Benjeddou <sup>7</sup>

- <sup>1</sup> Institute of Energy Infrastructure, Universiti Tenaga Nasional, Putrajaya Campus, Jalan IKRAM-UNITEN, Kajang 43000, Malaysia
  - <sup>2</sup> Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, Tronoh 32610, Malaysia
  - <sup>3</sup> Department of Civil Engineering, Engineering Architecture Faculty, Nişantaşı University, Istanbul 34398, Turkey
  - <sup>4</sup> Department of Architecture, Faculty of Engineering and Natural Sciences, Istanbul Sabahattin Zaim University, Istanbul 34303, Turkey
  - <sup>5</sup> Department of Civil Engineering, Mehran University of Engineering and Technology, Jamshoro 76062, Sindh, Pakistan
  - <sup>6</sup> Department of Civil and Environmental Engineering, Faculty of Engineering, Beirut Arab University, Beirut 11 5020, Lebanon
  - <sup>7</sup> Department of Civil Engineering, College of Engineering, Prince Sattam bin Abdulaziz University, Alkharj 16273, Saudi Arabia
- \* Correspondence: herda@uniten.edu.my (H.Y.B.K.); nakres42@yahoo.com (M.S.K.)



**Citation:** Katman, H.Y.B.; Khai, W.J.; Bheel, N.; Kırgız, M.S.; Kumar, A.; Khatib, J.; Benjeddou, O. Workability, Strength, Modulus of Elasticity, and Permeability Feature of Wheat Straw Ash-Incorporated Hydraulic Cement Concrete. *Buildings* **2022**, *12*, 1363. <https://doi.org/10.3390/buildings12091363>

Academic Editor: Łukasz Sadowski

Received: 21 July 2022

Accepted: 24 August 2022

Published: 2 September 2022

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**Abstract:** The extensive use of Portland cement (PC) in the manufacturing of concrete is responsible for the depletion of natural resources that are part of cement production. Cement supply is permanently threatened by the ongoing depletion of natural materials, including sand, limestone, and clay. Concurrently, the incineration of agricultural residues presents a significant ecological problem. This study explores the substitution of cement in concrete with 5%, 10%, 15%, and 20% wheat straw ash as an environmentally friendly alternative. The purpose of this investigation is to evaluate the effect of substituting wheat straw ash (WSA) for PC on the mechanical characteristics of concrete. A total of 75 concrete samples were made by cement or cement + WSA/fine aggregate/coarse aggregate ratio of 1:1, 5:3, and water-to-cement ratio was kept constant at 0.50. All of these specimens were cured and tested at 28 days. The properties tested in the paper were workability, compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, and permeability. The outcomes showed that the substitution of PC with WSA 10% resulted in the greatest concrete strength. In contrast, the mechanical properties and permeability of concrete were reduced when 20% WSA was substituted for PC at 28 days. In addition, the slump value dropped as increasing the content of WSA diminished the weight of PC in the concrete. This could be attributed to the fact that the water content in the WSA 20% concrete was not enough for mechanical strength. Other concretes with WSA showed similar properties to those of the WSA 10% concrete. It was concluded from the results that since the WSA 10% concrete showed the best properties, it can be recommended as the best recipe in this research work.

**Keywords:** energy; wheat straw ash-incorporated concrete; workability; strength; modulus of elasticity; permeability; modelling

## 1. Introduction

The demand for Portland cement (PC) is rising as a result of the widespread usage of concrete [1,2]. The current global cement consumption is estimated to be more than four

billion tons per year [3,4]. The production of cement is very dangerous to the environment because it generates a lot of heat and emits a lot of CO<sub>2s</sub> [5]. In the same way, the ingredients utilized to form PC also cause the depletion of our natural resources [6]. In fact, the use of natural resources such as natural aggregates (fine and coarse aggregates) and cement as a binder for concrete has led to the degradation of natural resources [7]. From an ecological perspective, the manufacturing of concrete is responsible for part of the greenhouse gas production. According to available data, the worldwide production of concrete is around 24 billion tons per year, which leads to a global emission of 7–10% of carbon dioxide into the atmosphere [8]. Given these concerns about the environment, the cost of building materials, the lack of available raw resources, and the demand for energy, the reuse of substitute solid waste has become a necessity to reduce these effects [9]. Therefore, using waste materials (e.g., agricultural waste) and industrial by-products in concrete to partially replace the cement has advantages and helps in reducing carbon dioxide emissions [10]. Research has shown that not only the environmental burden (e.g., safe disposal) is reduced, but in many cases, the properties of concrete are also developed [10]. It is perceived that the use of biomass [11] in concrete is very beneficial as it is not only financially viable but also brings improvements [12]. Recent research examined the use of bio-wastes (e.g., agricultural wastes) which have artificial pozzolanic properties in nature and can partially replace cement [13]. The researchers believe that using supplementary cementitious material (SCM) in concrete can help decrease the adverse environmental impacts associated with the cement or concrete manufacturing process [12,14]. By using such wastes as SCM in concrete, energy can be saved, and cement consumption can be reduced, thereby reducing carbon dioxide emissions into the environment [15]. Therefore, several supplementary cementitious materials have been carefully studied such as millet husk ash, coconut shell ash, groundnut shell ash, sugar cane bagasse ash [16], wheat straw ash [17], rice husk ash and saw dust ash [18], cement composite with wheat straw ash [19], concrete containing pre-treated wheat straw ash [20], palm shale oil [21], millet husk ash [22], silica fume [23,24], and corn cob ash [25,26].

Wheat is the world's principal cereal grain and a primary food supply for 2.5 billion people [27]. Worldwide, wheat production is estimated at around 750 million tons. When wheat is processed, large amounts of wheat straw waste are generated that are normally burnt in open fields causing environmental pollution, road traffic accidents (if burnt near public roads), and respiratory diseases [28,29]. Wheat straw ash (WSA) is the waste generated from burning the wheat straw. Scientific investigations have examined the function of WSA as a possible SCM in concrete [30–32]. In fact, the effectiveness of WSA as artificial pozzolanic material mainly depends on its physical and chemical composition [29,32]. WSA has a higher percentage of silica and higher fineness than cement; therefore, WSA may be considered a suitable supplementary cementing material in concrete. Some properties of hardened concrete are improved by the presence of WAS [31]; however, the tensile strength is generally lower [33,34]. To overcome this deficiency of concrete, different types of WSA generated by grinding and acid treatment are used in the concrete mixture. However, given the demand for affordable housing systems for rural and urban populations in developing countries, various programs have been proposed to reduce the cost of conventional building materials. One of the most innovative proposals is to find, develop, and substitute non-traditional local building ingredients, such as the prospect of utilizing certain agricultural waste and residues in building materials [35]. Therefore, many studies have been conducted on WSA as cement replacement material in concrete individually. For instance, the study published by Qudoos et al. in 2019 is an example of addition of WSA to cement-based material (CBM). Since the water-to-binder ratio was between 0.35 and 0.55 and three different sizes of WSA were used in the CBM, growing water-to-binder ratio produced a retarding in microhardness in the CBM. This negative impact was overcome with the accumulation of fine-sized WSA and silica fume powder. Researchers observed that the fine-sized WSA improved the microstructure of the interfacial transition zone of the CBM [36]. Al-Akhras and Abu-Alfoul [31] carried out another comprehensive research

which explained the impact of the WSA on hardened assets of autoclaved mortar. To measure the efficiency of the WSA, the researchers mixed mortar utilizing natural silica, wadi (a kind of local sand), and fine aggregate and substituted WSA for a mass of sand (3.6%, 7.3%, and 10.9%). The mortars were subjected to 2 MPa autoclave pressure for 2 h. They performed mechanical tests such as compressive, splitting tensile, and flexural strength. The results showed that those mortars including 10.9% replacement of limestone aggregate crushed with WSA had an 87% growth in compressive strength, 67% increase in splitting tensile strength, and a 71% increase in flexural strength when compared with the mechanical properties of the control mortar [31]. As can be understood from the papers mentioned above, there are a few comprehensive experimental works on the evaluation and modelling of properties of cement concrete incorporated bio-based in the extensive literature [37,38]. Therefore, the main goal of this investigation is to fill this gap by evaluating the fresh and mechanical properties of concrete, incorporating various percentages of WSA as cementitious material in the concrete and suggesting mathematical models for the properties.

### Research Significance

Concrete is the extensively preferred material in the construction industry. An abundance of industrial waste is produced at alarming rates from which the demand for efficient recycling processes emerges. Such efforts would allow waste materials to be repurposed as substitutes for natural resources, leading to sustainable practices. One of the most profusely available waste materials is wheat straw ash because wheat is processed every year around the world. Many studies have focused primarily on the replacement of cement with wheat straw ash in concrete mixes because of the surplus CO<sub>2</sub> emissions and increased costs associated with manufacturing cement and concrete. Nevertheless, none of the manuscripts produced a calibration equation for cement and concrete containing wheat straw ash. In addition, the current study presents workability, compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, and permeability of concrete with wheat straw ash.

## 2. Materials and Methods

### 2.1. Materials

The wheat straw was burnt at 570 °C to 670 °C under controlled burning preparation for five hours to produce wheat straw ash (WSA). After converting wheat straw into wheat straw ash (WSA), it was sieved using a 75 µm sieve to remove big particulates, and then, sieved ash was added to the mixture as a substitute for cement. Moreover, Portland cement (PC) was produced at a burning temperature of 1400 °C to 1450 °C, and it was utilized as binding material in the concrete. The oxides compositions of WSA and PC are detailed in Table 1. In addition, crushed stone with a 20 mm particle size was utilized as coarse aggregate (CA), while hill sand that passed through a 4.75 mm mesh was used as fine aggregate (FA). Table 2 gives the physical properties of aggregate. Furthermore, the sieve analysis of aggregate stack was carried out conforming to procedure ASTM C136 [39], and specific gravity and water absorptions of FA stack were performed under ASTM C128-15 [40]. Similarly, specific gravity and water absorptions of CA stack were performed by following ASTM C127-15 [41] consistently, and the bulk density test for the stack of fine aggregate and coarse aggregate was conducted according to ASTM C29/C29-17a [42]. In addition, potable water was employed for preparation and curing of experimental work.

**Table 1.** Oxides composition of WSA and PC.

Binder	Compound (%)					
	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	Na <sub>2</sub> O	SO <sub>3</sub>
WSA	67.34	6.44	4.36	10.60	0.47	1.85
PC	20.78	5.11	3.17	60.22	0.18	2.86

**Table 2.** Physical properties of aggregates.

Types of Aggregate	Physical Properties of Aggregates			
	Fineness Modulus (–)	Specific Gravity (g/cm <sup>3</sup> )	Bulk Density (Compacted) (kg/m <sup>3</sup> )	Water Absorption (%)
Fine aggregate	2.15	2.61	1845	1.3
Coarse aggregate	6.75	2.65	1630	0.75

## 2.2. Manufacturing of Concrete

This research was conducted on five mixtures including 0–20% of WSA as replacement for cement to evaluate the workability and mechanical characteristics (compressive, splitting tensile, and flexural strengths and modulus of elasticity and permeability) of the mixture. However, a total of 75 concrete specimens were made by cement or cement + WSA/fine aggregate/coarse aggregate ratio of 1:1, 5:3, and the water-to-cement ratio was kept constant at 0.50. In addition, one concrete mix was prepared with cement only and the remaining concrete mixes were prepared with 5–20% of WSA as replacement for PC. Table 3 indicates the mixture proportion of concrete; the percent of PC, WSA, FA, and CA; and the water-to-binder ratio.

**Table 3.** Mixture proportion of concrete.

Types of Concrete	Proportion of Mixture (kg/m <sup>3</sup> )					
	PC	WSA	Fine Aggregate	Coarse Aggregate	Water	Water-to-Binder Ratio
Control	373	0	560	1120	187	0.50
WSA 5%	354.3	18.6	560	1120	187	0.50
WSA 10%	335.7	37.3	560	1120	187	0.50
WSA 15%	317.05	55.95	560	1120	187	0.50
WSA 20%	298.4	74.6	560	1120	187	0.50

## 2.3. Testing Methods

### 2.3.1. Fresh State Testing (Slump Test)

It was carried out on the five mixtures of fresh concrete accumulation with various percentages of WSA as SCM by following the standard described in ASTM C143/C143M-15a [43]. The workability test was carried out on a slump test tray with a slump cone and a tamping rod. The test was performed three times for each mixture, and descriptive statistics, such as average and standard error and regression analysis were applied to the results of fresh state testing.

### 2.3.2. Mechanical Testing

The mechanical properties of concrete such as compressive strength, modulus of elasticity, permeability, splitting tensile strength, and flexural strength were achieved. However, the compressive strength was carried out on fifteen cubical specimens (100 mm × 100 mm × 100 mm) of mixture including control concrete and WSA-concrete under the rule of ASTM C39/C39M standard [44]. The splitting tensile strength was executed on fifteen cylinders (200 mm × 100 mm) made of concrete in Table 2 by following the ASTM C 496/C496M-17 standard rule [45]. Similarly, the flexural strength was tested through fifteen prisms (500 mm × 100 mm × 100 mm) of mixture, as shown in Table 2, by adhering to the rule of ASTM C293/293M-16 standard [46]. A universal testing machine was used for measuring the compressive, splitting tensile, and flexural strengths. In addition, permeability test was performed on fifteen cubical samples (100 mm × 100 mm × 100 mm) of concrete by obeying BS EN 12390-8:2019 [47], and the modulus of elasticity was checked through fifteen-cylinder specimens of concrete (200 mm × 100 mm) by using the and ASTM

C 469/C469M-14 [48]. All tests were carried out after 28 days of curing. A compressometer–extensometer combined with a digital dial gauge was used for measuring the modulus of elasticity. Results of statistical methods such as average and standard error were also evaluated, and regression analysis was performed between the mechanical properties and the permeability and slump tests to provide a calibration equation for the work.

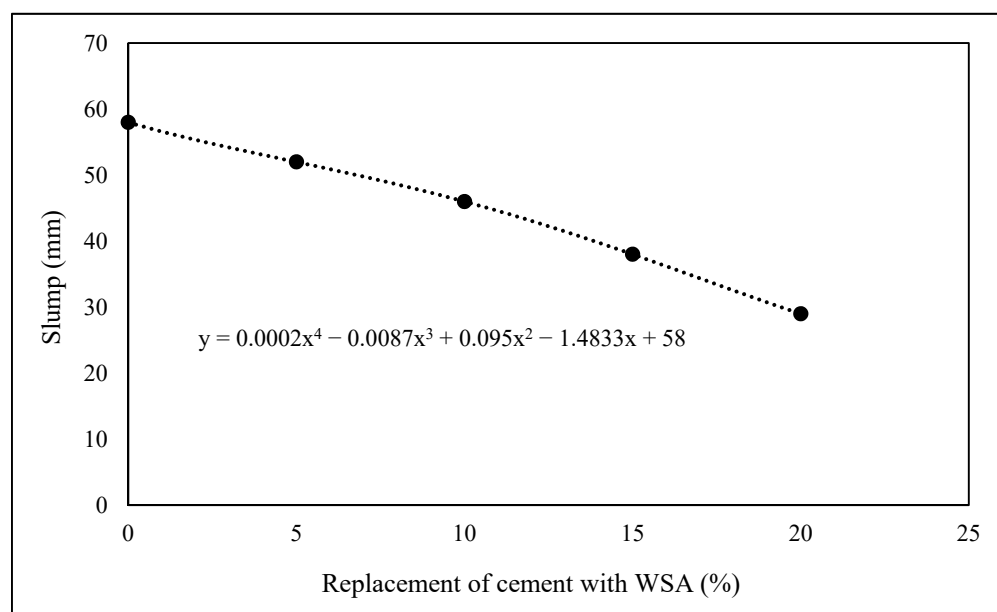
### 3. Results and Discussions

#### 3.1. Analysis of Concrete Incorporating Wheat Straw Ash as SCM

This section presents the results of experiments carried out on concrete specimens to evaluate the fresh and hardened properties of concrete, when WSA was used as SCM at replacement levels of 0%, 5%, 10%, 15%, and 20% by weight.

##### 3.1.1. Slump Test

Figure 1 depicts the workability of WSA concrete after the introduction several proportions of WSA as SCM. It is evident from the results that with rise in WSA content, the slump value declined. The reduction in workability of concrete could be due to the high surface area of WSA, which increased the amount of water required for enough workability. Moreover, because of the high water demand of the WSA, the concrete mixture absorbs a higher quantity of mixing water and thus makes the mixture harden resulting in lower workability. It was discovered that the 20% cement replacement of WSA decreased the slump of concrete by 50%. Once the cement was replaced with WSA at 5%, 10%, and 15% in the concrete mix, the slump decreased by 10.3%, 20.6%, and 34.4%, respectively.



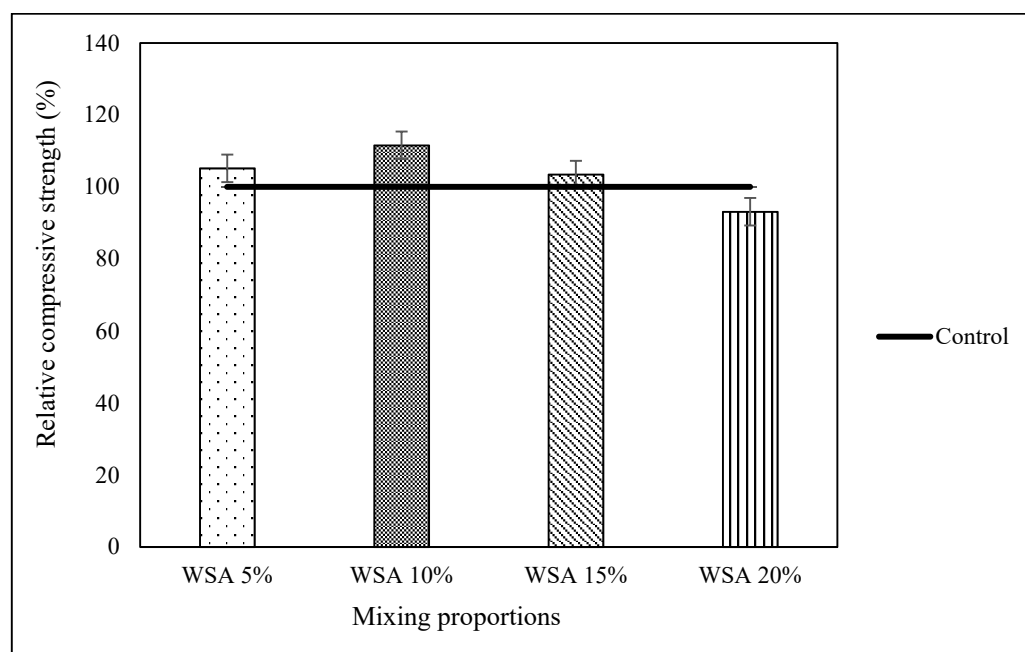
**Figure 1.** Workability of concrete containing wheat straw ash.

This reduction observation is in line with that of [31], in which the WSA was used as sand replacement material, and that of [49], in which the waste compact disk plastic was used as coarse aggregates (CA) substitution material in conventional concrete and self-compacted concrete. In slump, the reductions were, respectively, 31.7%, 43.5%, 64.7%, 74.1%, and 82.3% for 5%, 10%, 15%, 20%, and 25% replacement of aggregate with waste compact disc plastic in the concrete. A similar tendency like that of concrete containing the waste compact disk plastic as coarse aggregate was observed for fresh concrete mixes made by replacement of cement with the WSA [50–52]. The higher the WSA percent, the lower the workability of concrete. Additionally, it is reported in the available literature that the utilization of secondary cementing ingredients tends to decrease the workability characteristics of concrete due to the resulting stiffness in the concrete matrix [53–55].

However, the slump loss can be supplemented by using admixtures in the concrete, as a practical solution. On the one hand, there seems to be a good correlation between slump and replacement percent of cement with WSA (Figure 1). An equation with a correlation coefficient of  $R^2 = 1$  is presented in the in Figure 1. The lower the slump quantity, the higher the replacement percent of cement with WSA. This suggests that the WSA impacted concrete workability, resulting in lesser slump and higher water requirement. Without a doubt, the greater substitution percentage of WSA and the wide surface area of WSA required more binder paste and water to wrap around the WSA particles because of the strong bond between WSA and other components in the concrete mixture. A similar kind of research study was performed by Bheel et al. [56] which showed that the slump value declined to the extent WSA substituted the mass of PC in the concrete. Other comparable investigations were performed on the cementitious materials which reduce the workability of concrete [25,26].

### 3.1.2. Compressive Strength

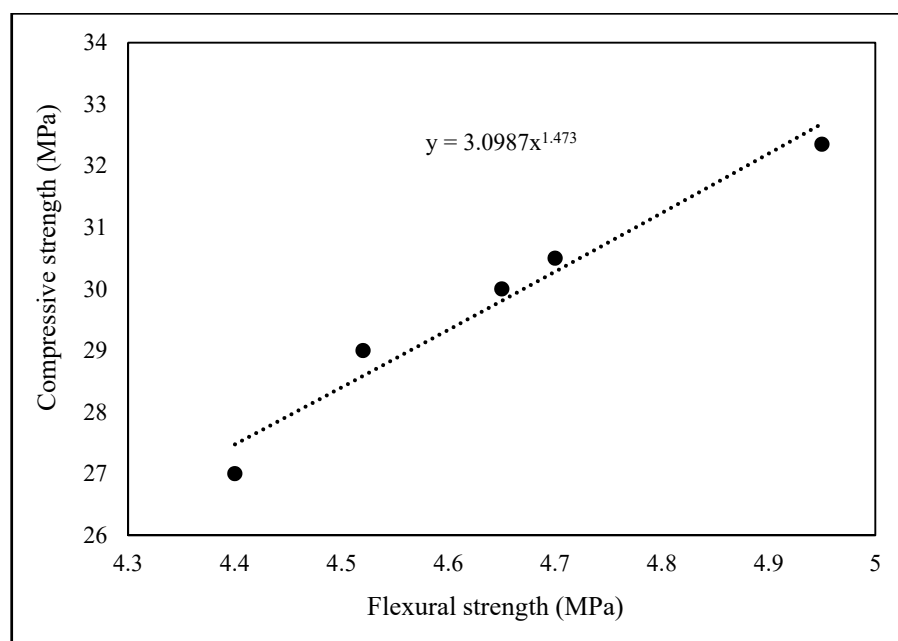
Compressive strength is known as the compression force carrying capacity of concrete before collapse. The compressive strength, as well as flexural strength test and splitting tensile test, is the most useful test, as it shows the most important characteristic of the concrete [57]. The relative compressive strength of conventional concrete and concrete with WSA as secondary cementing material and mixing proportions of concrete are shown in Figure 2. The findings show that the compressive strength of the WSA concrete was enhanced by the accumulation of WSA content. The 10% cement replacement with the WSA is the best prescription for the concrete mixture because it shows the highest compressive strength in the work, with more than 32 MPa. It must be at the optimum replacement level as well.



**Figure 2.** Relative compressive strength of conventional concrete and concrete with wheat straw ash and mixing proportions of concrete.

The strength of concrete was reduced at 20% cement substitution level with WSA. It was also clear that the compressive strength of concrete containing WSA up to 15% was larger than that of the control concrete (Figure 2). The results obtained in this study are in line with those obtained by Qudoos et al. [19] which recommended 20% replacement as optimum because the strength of concrete kept increasing with the addition of WSA which was subject to mechanical processing. Additionally, the high strength obtained in

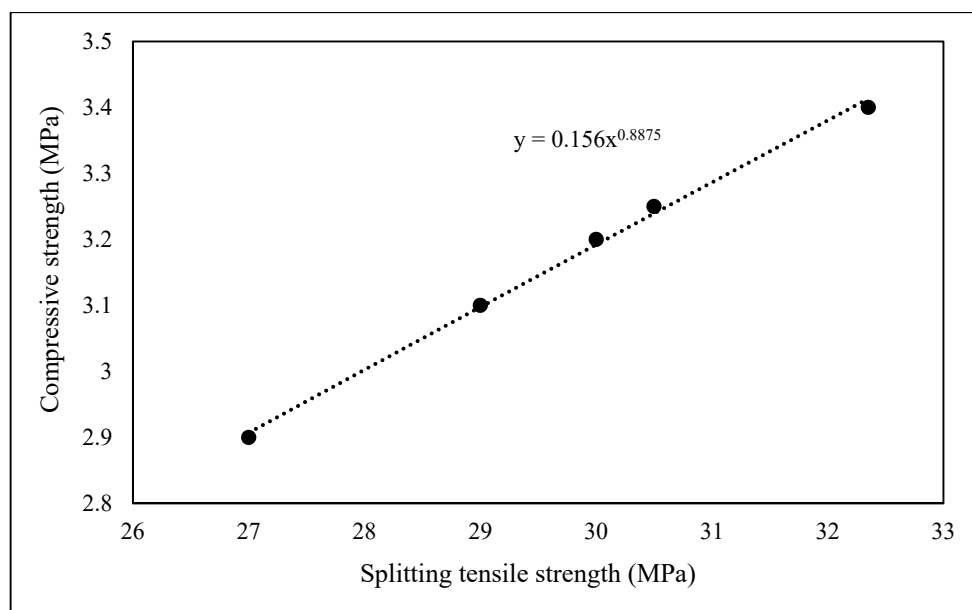
the present study is due to the pozzolanic effect of the WSA, despite the concrete mixture having a high water-to-cement ratio (i.e., 0.5). The WSA up to 20% retarded the compressive strength because the water content in the concrete mixture was not enough. However, the reduction in cement content per volume of concrete and the presence of coarse aggregate stack led to retardation in compressive strength in concrete with WSA 20%. It is also possible to identify that the optimum quantity of WSA can vary based on source of WSA, burning method of wheat straw and the composition of cementitious compound. Moreover, numerous studies related to the use of supplementary cementitious materials available in the literature recommend that replacing 10% of cement with WSA is the optimum level [8,55–61]. The mortar containing WSA particles instead of cement showed 20% greater compressive strength than that of the control cement mortar containing no WSA. This compressive strength growth was attributed by the authors to latent hydraulic impact and pozzolanic influence of the fine fraction of WSA particles in accordance with the microstructure densification [19,20]. Similar results to those of Qudoos et al. [19] were obtained by Qudoos et al. [36] who indicated that the accumulation of fine fraction of WSA improved the micro-hardness of the concrete by latent hydraulic effect and pozzolanic effect. The authors pointed that there are important enhanced physico-mechanical assets in mortar incorporating WSA as a partial substitute for fine fraction of aggregate [31]. For substitution levels of 3.6%, 7.3%, and 10.9% WSA with fine aggregate, the compressive strength was 12%, 75%, and 87% greater, respectively, when compared control mortar with no WSA [36]. Figure 3 shows a meaningful correlation between flexural strength and compressive strength, and an equation for estimation of 28th-day compressive strength from flexural strength.



**Figure 3.** A meaningful correlation between flexural strength and compressive strength, and an equation for estimation of 28th-day compressive strength from flexural strength.

There were many equations suggested for the flexural strength and compressive strength of cement-based material (CBM). For instance, a paper written by Ahmed et al. in 2008 [62] presented an equation between flexural strength and compressive strength, which is  $0.3f_c^{0.5} \leq f_r \leq f_c^{0.5}$  [62]. Geron and Paultre recommended three equations relating to estimate compressive strength of concrete from flexural strength, which are  $f_{r \min} = 0.68f_c^{0.5}$ ,  $f_{r \text{ avg}} = 0.94f_c^{0.5}$ ,  $f_{r \max} = 1.2f_c^{0.5}$  [63]. ACI Committee 363 participated in equation recommendation for strength estimation with  $f_r = 0.94f_c^{0.5}$  [64]. Finally, Mindess et al. gave an equation which is  $0.11f_c \leq f_r \leq 0.23f_c$  in 2003 [65]. Additionally, the equation

fills the gap between conventional concrete and concrete with WSA in Figure 7. Of all equations presented for flexural strength and compressive strength of concrete, the most important equation is the one in Figure 3 for concrete containing WSA because of the WSA additive which can provide strength gain for cement-based concrete. That equation in Figure 3 could open a new way to develop new method for measuring the compressive strength of concrete with WSA substitutions of 6%, 7%, 8%, 9%, 11%, 12%, and so on. It could be also used as a validation equation for a new green concrete system, as it is in the paper. Figure 4 shows a meaningful correlation between splitting tensile strength and compressive strength, and an equation for estimation of 28th-day compressive strength from splitting tensile strength.



**Figure 4.** A meaningful correlation between splitting tensile strength and compressive strength, and an equation for estimation of 28th-day compressive strength from splitting tensile strength.

There were also many equations suggested for splitting tensile strength and compressive strength of cement-based material (CBM). For instance, a paper written by Oluokun et al. [66] presented an equation for splitting tensile strength and compressive strength, which is  $f_{sp} = 0.294f_c^{0.69}$  [66]. Carneiro and Barcellos recommended three equations related to the estimation of compressive strength of concrete and flexural strength—which is  $f_{sp} = 0.34f_c^{0.735}$  [67]. ACI Committee 318 participated in equation recommendation for strength estimation with  $f_{sp} = 0.56f_c^{0.5}$  [68]. Carino and Lew are other authors who presented a significant equation regarding estimation of compressive strength from splitting tensile strength, which is  $f_{sp} = 0.272f_c^{0.71}$  [69]. Another equation was found by Raphael in 1984 [70], which is  $f_{sp} = 0.313f_c^{0.667}$ . Finally, Gardner et al. provided two equations in 1988 which are  $f_{sp} = 0.47f_c^{0.59}$  and  $f_{sp} = 0.466f_c^{0.66}$  [71]. Additionally, the equation fills the gap between conventional concrete and concrete with WSA in Figure 4. Of all equations presented for splitting tensile strength and compressive strength of concrete, the most important equation is for concrete containing WSA (Figure 4) because the WSA additive can provide splitting tensile strength gain for cement-based concrete. That equation in Figure 4 could open a new way to develop a new method for measuring both the compressive strength splitting tensile strength of concrete for WSA substitutions of 6%, 7%, 8%, 9%, 11%, 12%, and so on. This equation could also be used as a validation equation for a new green concrete system, as shown in the paper. On the one hand, the filler effect and pozzolanic behavior of WSA increased the compressive strength of concrete up to a 15% replacement level. However, with the increase in WSA content and decrease in cement quantity, the calcium hydroxide required to react with silica was reduced, which resulted

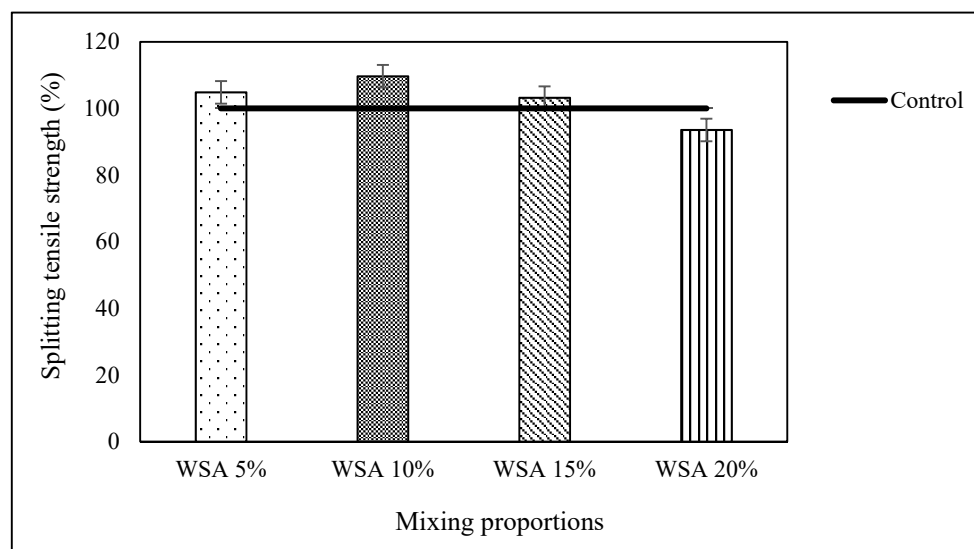
in lower strength in concrete with WSA 20%. It is pertinent to consider that the strength of concrete was more than that of the control mix (compressive strength of 29 MPa) for all replacement levels, except for 20% replacement, where concrete had compressive strength of 27 MPa. In conclusion, WSA concrete can be utilized for structural applications as it possesses compressive strength of more than 30 MPa at the cement replacement levels and on 28 days of curing.

### 3.1.3. Splitting Tensile Strength

Splitting tensile strength of concrete is one of the most important factors for understanding failure and minimum resiliency. Many design standards for mixing concrete do not use the splitting tensile strength as a parameter of cracking strength. This paper presents an experimental work on data points from a large number of research programs with concrete splitting tensile strengths ranging from 2.9 to 3.4 MPa. Figure 5 shows the relative splitting tensile strengths of conventional concrete and concrete with WSA and mix proportions of concrete. In this experimental work, the tensile efficacy of concrete blended with WSA is evaluated through the indirect tensile strength test, also called the splitting tensile strength test. It can be concluded from Figure 5 that the splitting tensile strength of concrete increased with the increase of WSA content, except for concrete with WSA 20%. It has been detected in the results that the splitting tensile strength of the WSA concrete was augmented with the accumulation of WSA content. The 10% cement replacement with the WSA is the best prescription for the concrete mixture because it shows the highest splitting tensile strength in the study (3.4 MPa). This must be the optimum replacement level as well. The results obtained in this study are in line with those obtained by Qudoos et al. which recommended 10% replacement as optimum because the strength of concrete kept increasing with the addition of WSA [72]. Additionally, the high strength obtained in the present study is due to the pozzolanic effect of the WSA, despite the concrete mixture having a high water-to-cement ratio (i.e., 0.5). The WSA up to 20% retarded the splitting tensile strength because the water content in the concrete mixture was not enough. However, the reduction in cement content per volume of concrete and the presence of coarse aggregate stack led to the retardation in splitting tensile strength in the concrete with WSA 20%. The concrete containing 10% WSA particles instead of cement showed 9.6% greater splitting tensile strength than that of the control concrete containing no WSA. This growth of splitting tensile strength was attributed by the authors to a latent hydraulic impact and pozzolanic influence of the fine fraction of WSA particle in accordance with the microstructure densification [19,20]. In addition, WSA-based concrete was not classified in accordance with the splitting tensile strength. In the study, if the splitting tensile strength is less than 3 MPa, it is classified as very highly deformable; if the splitting tensile strength is between 3–3.5 MPa, it is sorted as highly deformable; if the splitting tensile strength is among 3.5–4 MPa, it is sorted as moderately deformable; if the splitting tensile strength is between 4–5 MPa, it is classified as lowly deformable; and if the splitting tensile strength is over 5 MPa, it is sorted as very lowly deformable. Because the splitting tensile strength increased from 2.9 MPa to 3.4 MPa with increasing of the WSA content in the concretes, the concrete is in the sorting as moderately deformable.

It is also evident that the splitting tensile strength of concrete with WSA up to 15% is also greater than that of the control (Figure 5). However, it was retarded after 15% cement replacement with WSA. The splitting tensile strength gain of concrete with WSA is due to the contact of reactive silica provided by WSA with calcium hydroxide in the pore solution of concrete. Additionally, the high strength obtained in the current work is due to the pozzolanic effect of the WSA, despite the concrete mixture having a high water-to-cement ratio (i.e., 0.5). The WSA up to 20% retarded the splitting tensile strength because the water content in the concrete mixture was not enough. However, the reduction in cement content per volume of concrete and the presence of coarse aggregate stack led to the retardation in splitting tensile strength in concrete with WSA 20%. However, beyond a 15% replacement of cement with WSA, the reduction in cement content may result in lesser production of

hydration products than that of the control. Nevertheless, it is evident from Figure 5 that there is a negligible difference between splitting tensile strength of the control specimens and that of the specimens with maximum replacement level of cement with WSA, e.g., 20% in this mixture. Figure 4 shows a meaningful correlation between splitting tensile strength and compressive strength, and an equation for estimation of 28th-day splitting tensile strength from compressive strength.



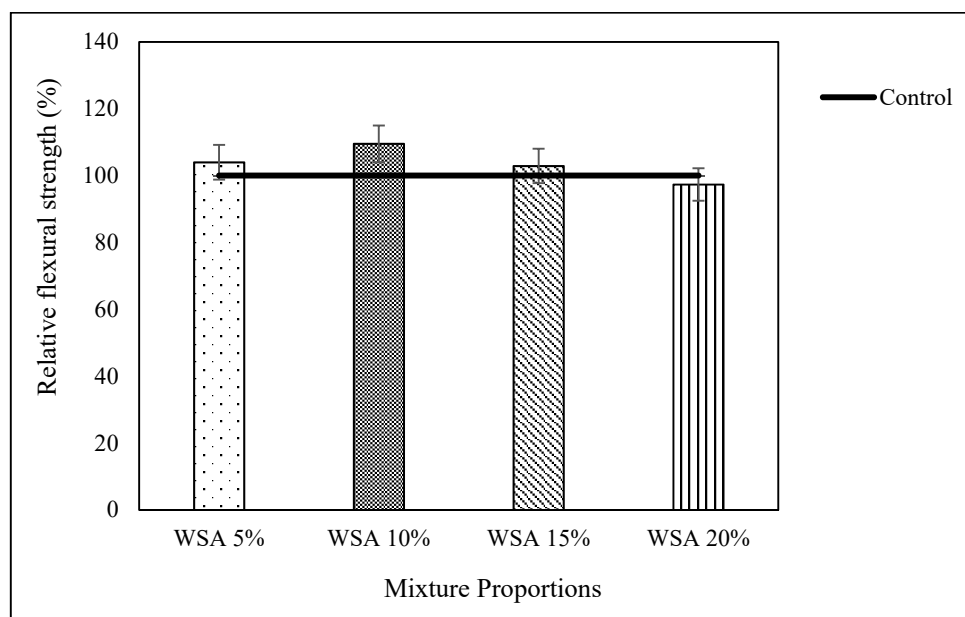
**Figure 5.** Relative splitting tensile strength of conventional concrete and concrete with wheat straw ash and mixing proportions of concrete.

There were numerous equations that helped in analyzing the connection between the splitting tensile and compressive strengths of conventional concrete that were derived from the earlier research mentioned in Section 3.1.2 (compressive strength). The stress of tensile strength splits the structure of concrete leading to loss of contact between WSA powder and aggregate and binder at the failure stage. As can be seen in Figures 4 and 5, the efficiency of WSA is a significant function of the mechanical strength of concrete. Therefore, WSA may be helpful as a pure tensile component in concrete. The correlation result between the compressive and splitting tensile strengths of the concrete with WSA helps support this suggestion strongly.

#### 3.1.4. Flexural Strength

Figure 6 demonstrates the effect of WSA content as SCM on flexural strength of concrete. It is evident from the attained fallouts that the relative flexural strength of the WSA concrete was improved with the accumulation of WSA content. The 10% cement replacement with WSA is the best prescription for the concrete mixture because it shows the highest flexural strength in the study, with more than 4.95 MPa. The results obtained in this study are in line with those obtained by Qudoos et al. [72] which recommended 10% replacement as optimum because the flexural strength of concrete kept increasing with the addition of WSA. Additionally, the high strength obtained in the present study is due to the pozzolanic effect of the WSA, despite the concrete mixture having a high water-to-cement ratio (i.e., 0.5). WSA up to 20% retarded the flexural strength as expected since the water content is not enough for the concrete mixture that includes WSA. However, the reduction in cement content per volume of concrete and the presence of coarse aggregate stack led to the retardation in flexural strength in concrete with WSA 20%. The concrete containing 10% WSA particles instead of cement showed 9.5% greater flexural strength than that of the control concrete containing no WSA. This growth of flexural strength was attributed by the authors to latent hydraulic impact and pozzolanic influence of the fine fraction of WSA particles in accordance with the microstructure densification [19,20]. In addition,

WSA-based concrete was not classified in accordance with the flexural strength. In this study, if the flexural strength is less than 4 MPa, it is classified as very highly deformable; if the flexural strength is between 4–4.5 MPa, it is sorted as highly deformable; if the flexural strength is among 4.5–5 MPa, it is sorted as moderately deformable; if the flexural strength is between 5–5.5 MPa, it is classified as lowly deformable, and if the flexural strength is over 5.5 MPa, it is sorted as very lowly deformable. Because the flexural strength increased from 4.4 MPa to 4.95 MPa with the increase in WSA content in the concretes, they are sorted as moderately deformable.

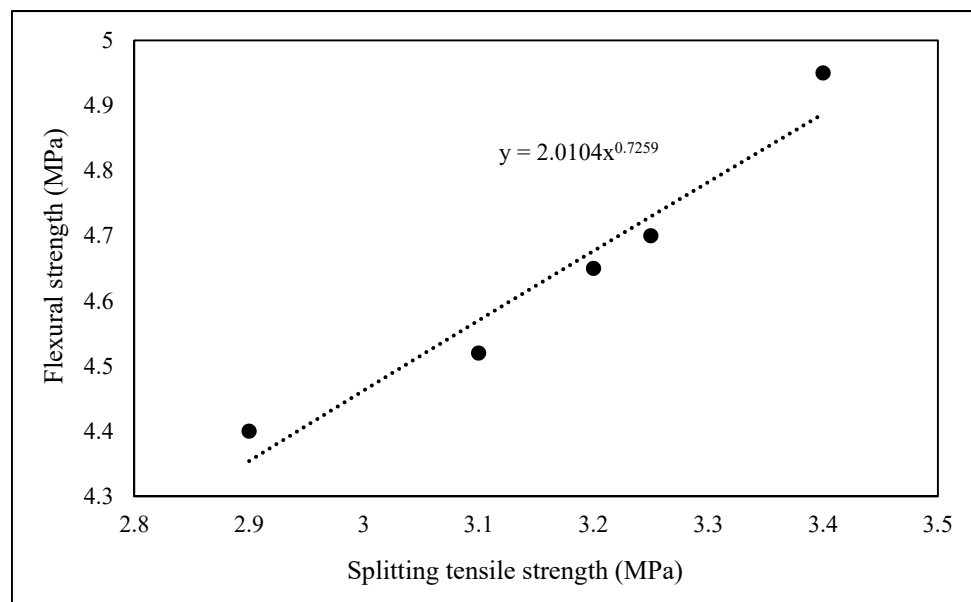


**Figure 6.** Relative flexural strength of concrete containing wheat straw ash.

It must be the optimum replacement level as well. The flexural strength of concrete is reduced at 20% cement replacement level with WSA. It is also evident that the flexural strength of concrete with WSA up to 15% is also greater than that of the control (Figure 6). The results obtained in this work are in line with those obtained by Qudoos et al. [19] who recommended development in the 28th-day of flexural strength of cement-based material made by replacing cement with 16% WSA. It is concluded from the obtained results that flexural strength development followed a similar trend as that in compressive and splitting tensile strengths—the flexural strength was enhanced up to a 15% replacement level. Finally, it was retarded with the increase in WSA content in the concrete mixture. Thus, it can be concluded that the accumulation of WSA content does not have any unfavorable influence on the progress of hydration kinematics, except for the 20% replacement level which gave the flexural strength lower than that of the control. This could be due to the dilution effect of WSA on the cement which disturbed the interfacial transition zone and affected the strength in the long run. Additionally, as is known from the literature, the performance of cement-based material containing WSA 24% was an effective solution regarding on the detrimental chemical effect of sodium sulfate being in marina environment as well as being advantageous of 8% WSA in relating to magnesium sulfate environment [19].

Considering the data determined from concrete containing the WSA, this regression analysis is very useful in terms of the relationship between the flexural and splitting tensile strengths because it could open a new way for predicting the flexural strength of an intermediate quantity of WSA concrete. Between the various forms of regression equations assessed, the power equation form in Figure 7 was deemed to be the most appropriate because the coefficient of determination was high. Therefore, it could be perfect to utilize the flexural strength for assessing the splitting tensile strength of the concrete with WSA. Many comprehensive investigations have revealed that the content of concrete can affect

the relationship between the flexural and splitting tensile strengths. Hence, the content of concrete was measured in this study. Accordingly, this factor enhanced the splitting tensile strength estimation importantly.

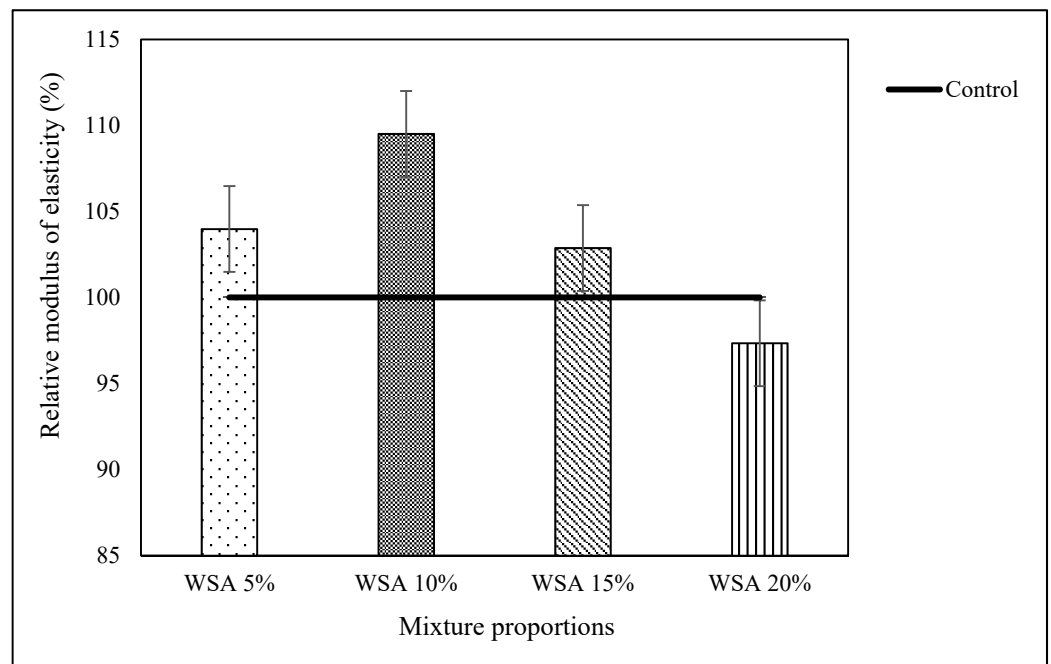


**Figure 7.** A meaningful correlation between flexural strength and splitting tensile strength, and an equation for estimation of 28th-day flexural strength from splitting tensile strength.

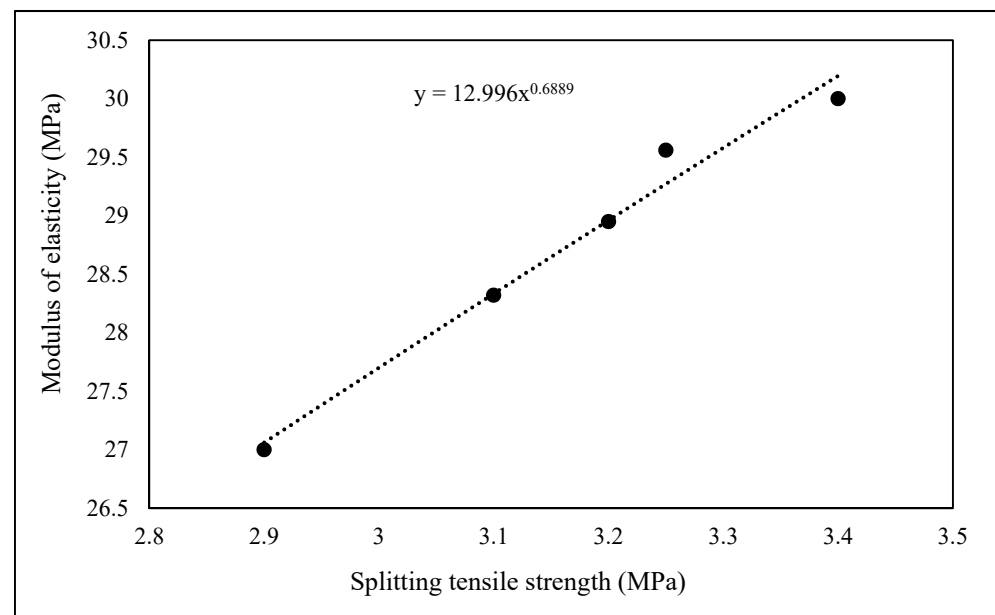
### 3.1.5. Modulus of Elasticity (MOE)

It indicates the stiffness or resistance to possible deformation, which means that the higher the elastic modulus of the concrete, the higher the resistance to deformation. Figure 8 demonstrates the impact of WSA as a SCM on the relative MOE of concrete. Biricik et al. reported that stronger pozzolanic characteristics in WSA, as well as a silica concentration of 73% when conditioned at 670 °C (relative to 570 °C), result in better mechanical strength for cement-based composites [30]. Ataie and Riding noted that once the silica content of WSA increased to 86.5%, due to the surface treatment of wheat straw before its firing, the mechanical strength of the concrete increased as well [73]. Qudoos et al. found that grinding WSA for at least 60 min decreased particle size while increasing amorphousness and Blaine's specific surface area [36]. Therefore, that grinding process of WSA helped increase the mechanical properties of concrete in an important way.

It is evident from results that the MOE of concrete was improved by the increase in WSA content due to pozzolanic reactions between the binders (cement and WSA) and continuous hydration. It has been reported in the literature that the improvement in MOE of concrete with accumulation of WSA can be attributed to the possible refinement of the concrete pores. This aided in the development of stronger interfacial bonds between the aggregates and the binder, i.e., WSA and cement [8]. Some materials were classified in accordance with the MOE. In this classification, if the MOE was less than 5 MPa, it was classified as very highly deformable; if the MOE was between 5–15 MPa, it was sorted as highly deformable; if the MOE was among 15–30 MPa, it was sorted as moderately deformable; if the MOE was between 30–60 MPa, it was classified as lowly deformable; and if the MOE was over 60 MPa, it was sorted as very lowly deformable. Because the MOE increased from 27 MPa to 30 MPa by increasing the WSA content in the concrete, this concrete is classified as moderately deformable [74]. Figure 9 shows a meaningful correlation between the MOE and splitting tensile strength, and an equation for estimation of 28th-day MOE from splitting tensile strength.



**Figure 8.** Relative modulus of elasticity of concrete with wheat straw ash and replacement proportions of common cement with wheat straw ash.

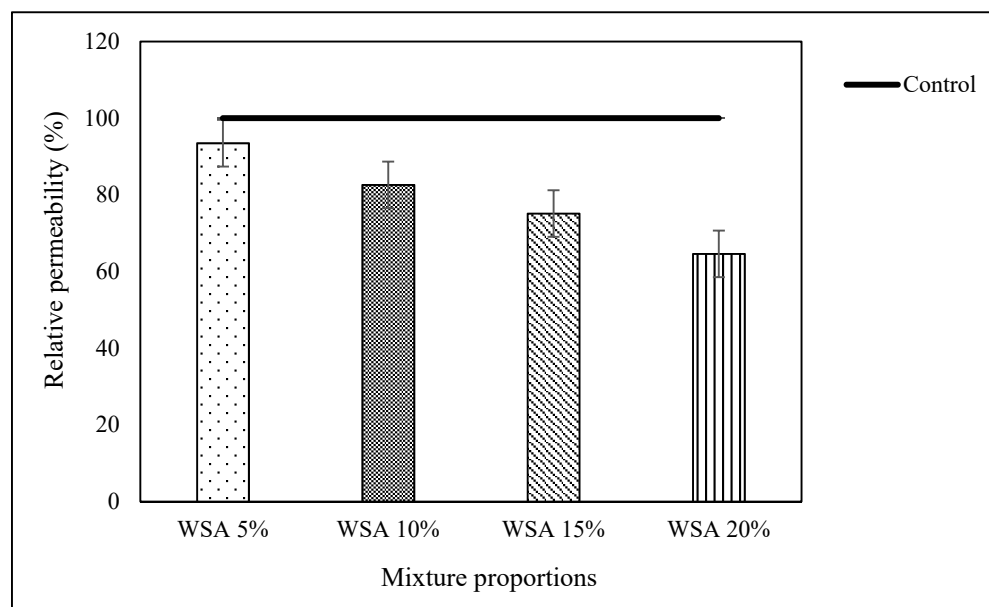


**Figure 9.** A meaningful correlation between the modulus of elasticity and splitting tensile strength, and an equation for estimation of 28th-day modulus of elasticity from splitting tensile strength.

To estimate the MOE from splitting tensile strength, there are no equations that help estimate the relationship. To that aim, An equation is presented for the MOE and splitting tensile strength of concrete in Figure 9. The most important equation is in Figure 9 for concrete containing WSA because the WSA additive can provide strength gain for cement-based concrete. That equation in Figure 9 could open new ways to develop a new method for measuring the MOE of concrete with WSA substitutions of 6%, 7%, 8%, 9%, 11%, 12%, and so on. This could be also used as a validation equation for a new green concrete system, as shown in the paper.

### 3.1.6. Permeability

The permeability of concrete blended with WSA as supplementary cementitious material was evaluated in terms of water penetration depth of concrete specimens subjected to water under pressure. Figure 10 shows the relative permeability of concrete containing 5%, 10%, 15%, and 20% WSA by weight of cement. To obtain useful artificial pozzolanic ash from WSA, Biricik et al. specified that the most usual firing process could be set up to be between 570 °C and 670 °C for five hours, in which grey and white particles turn out the burnt ash completely [36]. Al-Akhras and Abu-Alfoul also indicated that as the wheat straw, which was fired at 650 °C for twenty hours and then pulverized for two hours [31], developed the amorphous content of WSA by extracting alkalis and organic compounds, the ash decreased the permeability of the concrete as well. In addition, once the WSA was treated within acid at 80 °C for twenty-four hours, dried before firing in an electrical furnace at 650 °C for six hours, and pulverized for one hour in a laboratory ball mill, the produced WSA had a silica content of 86.5%, loss of ignition of 1.2%, a Blaine surface area of 65 m<sup>2</sup>/g, and an amorphous content of 99.3% [73]. At the same time, Ataie and Riding [73] supported the findings of Biricik et al. and Al-Akhras and Abu-Alfoul regarding permeability [30,31].

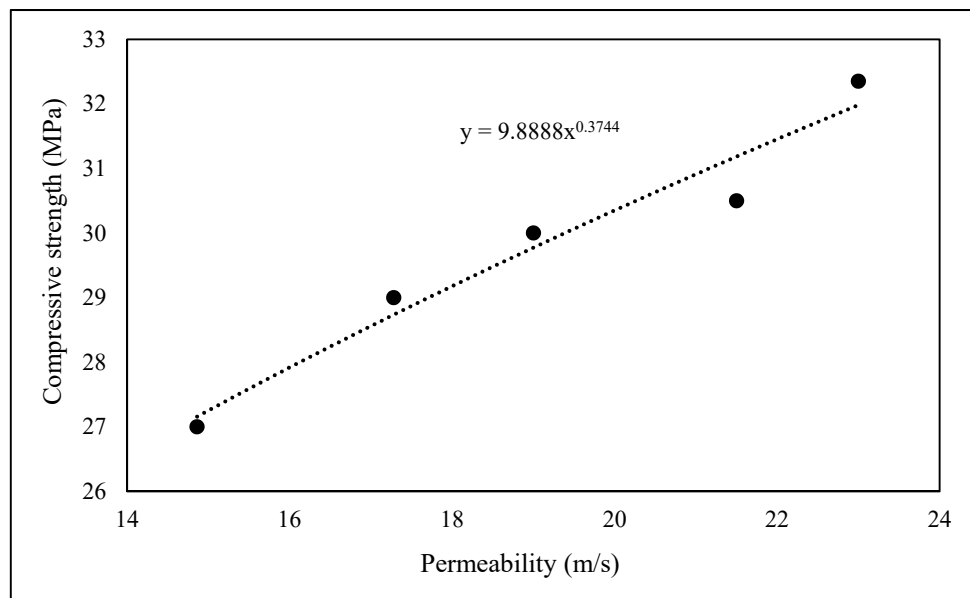


**Figure 10.** Relative permeability of concrete with wheat straw ash and replacement ratio of cement with wheat straw ash.

The specimens were split, and afterwards, the water penetration depth was noted in line with the guidelines for assessing the permeability of WSA-concrete. The permeability of concrete was noted as 23, 21.5, 19, 17.28, and 14.86 mm for 0%, 5%, 10%, 15%, and 20% WSA concrete, respectively. The results show that the incorporation of WSA in the concrete mix reduced concrete permeability. This observation is in line with those of Biricik et al. where the permeability was dropped by 29% with utilization of metakaolin as cementitious material and Bheel et al. where WSA was used as cementitious material in concrete [8,19]. Figure 11 shows a regression relationship between the permeability and the compressive strength of concrete with WSA, and a mathematical equation.

To evaluate the compressive strength from the permeability of concrete, there were various conventional equations in previous studies. However, a powerful equation was presented in Figure 11. It will also help researchers and scientists to find new methods related to permeability and compressive strength of concrete. Because the correlation between permeability and compressive strength is very powerful, its reliability is also much higher than that of similar equations in the literature. However, the stress of compression

breaks the structure of concrete which included minor and major voids that can absorb water and lead permeability in concrete. After the water curing period, water absorption led to an increase in pressure between WSA powder-binder and aggregate, whose failure was shown in the strength test.



**Figure 11.** Regression relationship between the permeability and the compressive strength of concrete with wheat straw ash, and a mathematical equation.

#### 4. Conclusions

The aim of the present work was to evaluate the feasibility of using wheat straw ash as a supplementary cementitious resource to reinforce concrete to determine its freshness and mechanical properties. The results showed that the replacement of cement with WSA resulted in a stiffer concrete. The key points are summarized below:

- The workability of concrete declined as the quantity of PC substituted with WSA in concrete increased.
- The compressive, splitting tensile, and flexural strengths were enhanced at 10% of WSA while the lowest compressive, splitting, and flexural strengths were observed at 20% WSA substituting the mass of PC in the concrete after 28 days, respectively. However, the strength of concrete increased when WSA substituted the mass of PC by up to 10%, and then it started to drop.
- The modulus of elasticity was enhanced by utilizing the WSA as cementitious material up to a certain limit, and by further addition, to a certain limit, of WSA to the concrete, the modulus of elasticity was reduced after 28 days of curing.
- The use of wheat straw ash could also bring a financial benefit to the producers due to the obvious increase in production and to the demand from the construction sector. With such an approach, the disposal of waste wheat straw could also be practiced without compromising the ecology of planet.
- The permeability of concrete was reduced as the content of WSA substituting the mass of PC increased at 28 days.
- The available literature suggests that WSA is absorbent due to the presence of surface pores, and hence, its use in structural applications is highly recommended for developing the durability and mechanical properties of concrete structures.
- Moreover, as can be gleaned from the mathematical equations presented in the paper, the efficiency of WSA is a significant function of the mechanical strength of concrete. Therefore, WSA could be beneficial for the durability of concrete. The correlation

results between the strengths and between permeability and slump and strengths of the concrete with WSA strongly support this suggestion.

- Because the manuscript also offers a prescription for manufacturing cement with wheat straw ash, it opens new ways for scientists, readers, and graduate and post-graduate students as well as manufacturers of cement and concrete. Moreover, by expanding on the current state-of-the-art of properties and behaviors of cement and concrete containing wheat straw ash, it inspires future research and finds further support for practical applications.

**Author Contributions:** Conceptualization, N.B., A.K. and M.S.K.; methodology, N.B.; software, N.B.; validation, A.K.; data curation, N.B.; writing—original draft preparation, N.B. and M.S.K.; writing—review and editing, H.Y.B.K., W.J.K., J.K. and O.B.; visualization, M.S.K. and N.B.; supervision, M.S.K.; funding acquisition, H.Y.B.K. and W.J.K. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by Universiti Tenaga Nasional and grant number is J510050002-IC-6 BOLDREFRESH2025-CENTRE OF EXCELLENCE.

**Institutional Review Board Statement:** J510050002-IC-6 BOLDREFRESH2025-CENTRE OF EXCELLENCE.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

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

**Collaborators:** Universiti Tenaga Nasional, Malaysia and Nişantaşı University, Turkey.

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