Innovations

Mechanical Properties of Concrete Incorporating Teff Straw Ash as Cementitious Material

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Abstract

The production of cement results in the loss of natural resources, massive energy consumption, and environmental CO_2 emissions that contribute to global warming and climate change. In order to solve the issue researchers are becoming more interested in finding an alternate material to partially replace cement with industrial and agricultural wastes. Therefore, the purpose of this study was to investigate the potential of using Brown Teff Straw Ash (BTSA) as partial replacement for ordinary Portland cement (OPC) in the production of C-30 concrete. Concrete mixtures were created by partially replacing cement with BTSA in varying weight ratios (0%, 5%, 10%,15% and 20%) while maintaining a constant water-to-cement ratio of 0.5. Concrete test samples were put through testing for consistency, setting time, workability, compressive strength, water absorption, and flexural strength. The test findings showed that the workability exhibited a decreasing trend as the percentage of BTSA component increased, with recorded slump flow values ranging from 27 to 42 mm. contrarily, an increase in BTSA content was accompanied by a trend towards longer setting times for concrete mixtures. Initial and final setting times were between 62.5 and 110 minutes and 295 and 490 minutes, respectively, which is within the acceptable range. Concrete's compressive strength declined as the proportion of BTSA increased; the findings for the 28th day sample with 5% and 20% of BTSA, respectively, were measured at 38.14-22.16 MPa. However, it increases as the curing days increase, whereas the water absorption of the concrete increases as the BTSA increases but decreases as the curing days increase due to the porous nature of the BTSA. From the study, the results for flexural strength indicated a falling trend with a rise in BTSA's share. In general, it was also observed that, from the compressive strength, the concrete satisfies its design strength up to 10% replacement level without compromising the performance of concrete.

***Keywords**: compressive strength, flexural strength, water absorption, concrete, Teff straw ash*

1. Introduction

For decades, concrete has been used with admiration over the world[1]. Cement paste and fine and coarse aggregates are combined in specific ratios to create the man-made material known as concrete[2].Construction is directly or indirectly connected to the production of concrete, which results in the extensive extraction of natural resources[3][4].

Hence, it is essential to reduce degradation of natural materials and resources[5]by introducing cheap and waste materials having pozzolanic properties with the prospect to replace conventional materials of concrete[6].In the production of concrete, the aggregate is formed of sand, gravel, or crushed stone, while the paste is composed of cement, water, and additional cementitious and chemical admixtures.

The aggregates are joined together by the paste. Since the aggregates make up 70% to 80% of the concrete by mass, it is reasonable to expect that they will have an impact on its qualities[7].Cement is the binder and most expensive component of concrete, which is also an environmentally unfriendly element due to the release of CO_2 gas into the atmosphere and ecological devastation.

One tone of Portland cement releases about one ton of CO_2, which has serious environmental consequences[8].A significant source of CO_2 and other greenhouse gases is the manufacturing of Portland cement clinker, which accounts for 5-7% of the world's yearly CO_2 emissions[9][10][11].In order to reduce manufacturing costs and carbon dioxide emissions, researchers are examining the possibility of partially replacing cement with agricultural or industrial wastes, such as blast furnace slags, wheat straw ash, rice husk ash, fly ash, glass powder, and others[12].

In order to lessen the impact of greenhouse gases and manage waste disposal issues, such industrial by-products are being used globally as partial substitutes for cement in concrete. This creates a cleaner environment and sustainable concrete for use in the construction industry[13].The introduction of supplementary cementitious elements that maintain the mechanical qualities of cement and other related components is therefore required by the construction industry for modern concrete infrastructure.

Supplementary cementitious materials (SCMs) are pozzolanic elements that can optimize the engineering features of concrete, such as strength and durability[4].Industrial waste is classified as cementitious if it participates in a hydration reaction to react chemically; otherwise, it is classified as non-cementitious and inert waste[14].

Concern over the scarce and exhaustible nature of the basic materials used to produce concrete is growing on a global scale. It ought to be protected for upcoming generations.Due to this, the trends in construction materials have changed from being natural to being more artificial and a combination of both, and each has its uses. Since a few decades ago, byproducts and wastes have been used in a variety of civil engineering applications.

Recently very few Ethiopian and other researchers conducted teff straw as a possible replacement product for construction in dustries like Evaluation of Strength and Durability Concrete Properties using Teff Husk[15],Nano Silica-Based Teff Straw as an Eco-Friendly Substitute for Special Concrete[16],Experimental Investigation on the Effect of Teff Straw Fiber and Lime on Strength and Compressibility of Black Cotton Soil[17].But, detail investigation on the mechanical Properties of Concrete Incorporating Teff straw Ash is not conducted as the abundancy of the productin Ethiopia is very high.

Regarding material abundancy, Teff is common flour used for making the traditional food in Ethiopia. Teff is a main food for millions of Ethiopians, and statistics from the country's food and agricultural organization indicates that production is rising at an average yearly rate of 10.42% [15].The northern Ethiopian highlands are the centerof origin and diversity for the ancient tropical cereal crop known as teff (Eragrostis teff), which is said to have been domesticated there[18][19][20].Teff is a grain crop that is widely grown in Ethiopia, with an estimated 2.8 million hectares covered each year[18].

The area used for teff farming keeps expanding, and more farmers are doing so.Teff was grown by around 6.3 million farmers in 2013 as compared to 4.4 million farmers in 2001/2002.Similarly; teff area planted increased from 1.8 million hectares in1997 to 2.7 million hectares in 2013.Teff can be grown in a variety of agroclimatic conditions, including elevations ranging from sea level to 2800 meters above sea level, and in a wide range of soil, moisture, and temperature conditions[18][21].

The solid byproduct of Teff cereal is called Teff Straw Ash (TSA). Teff Straw is widely available, although little attention has been paid to it.Teff straw is produced in the greatest quantities, accounting for around 6.93% of the nation's total production of cereal crop straw[18].Every year, in Ethiopia more than 2 million tons of teff straw are discarded as garbage[22][23][24].

The chemical composition of TSA depends on the burning temperature, chloride, moisture content, loss on ignition, and silica content. For White Teff Straw Ash (WTSA),The combined chemical composition (SiO2,Al2O3,Fe2O3) for WTSA at600°C is 31%which is less than 50%[25]. As a result, WTSA does not meet the criteria to be classified as a pozzolanic material per ASTM C- 618 requirements and cannot be utilized to replace cement in construction[25].

The shared chemical composition (SiO2,Al2O3,Fe2O3)for (Brown Teff Straw Ash) BTSAat600°Cis65.12%which is greater than50% and will be regarded as Class C pozzolanic materials as per ASTM C- 618requirements[25].The shared chemical composition (SiO2,Al2O3,Fe2O3) for BTSA at750°C is 77.59%which is greater than 70% and will be regarded as Class F pozzolanic materials as per ASTM C- 618 requirements[25].

The shared chemical composition (SiO2,Al2O3,Fe_2O_3) for BTSA at900°Cis 70.64%which is greater than 70% and will be regarded as Class F pozzolanic materials as per ASTM C- 618requirements[25]. The silicate amount of the BTSArises when temperature increases from 600°C to750°C and declines from 750°Cto 900°C[25]. Due to mineral degradation at high temperatures, the amount of silicate at 900°Cdecreased[25][26].

TSA must meet ASTM C618-19 chemical composition standards in order to be used as pozzolan in cement and concrete. According to ASTM C618-19, any materials with a pozzolanic index of 70% or higher may be utilized as a supplementary cementitious material (SCMs). Hence BTS A with burning temperature above 750°C canbeusedas a supplementary cementitious material (SCMs).

Although Teff Straw is widely available in Ethiopia, only very few previous researches tried to investigate the effect of TSA on engineering properties of concrete. However, the effect of TSA on the mechanical properties of concrete is not yet sufficiently discovered. Determining the effects of engineering properties (consistency, setting time, slump for workability, compressive strength, water absorption, and flexural strength, as well as compressive strength relationships with that of density, flexural strength and water absorption) of concrete containing BTSA as a partial replacement for cement is the main goal of the study under consideration.

2. Materials and Experimental Methods

2.1.*Materials*

2.1.1.*Cement.* For this study, OPC cement of Derba Cement Company with a grade of 42.5R is used, which is available in our nearest construction material laboratory. It is assured that the cement is dry and free of lumps before it is added to the concrete mixture. The physical characteristics, such as consistency, setting times, and workability, are in accordance with the standards specified by ASTM C 150, as is the grading. For all of the trial mixes, the same brand of cement was utilized, and the amount put to each mix remained constant.

2.1.2.*Teff Straw Ash (TSA).* For this study, the Teffstraw is collected from Betelhem, south-Gondar zone, Ethiopia. the study was conducted on the burning of Teffstraw and identified the suitable burning and residence time to be 700°C -750°C.The higher temperatures will result in more silica content, but that silica will be in a crystalline form that is not active since the ash has broken down into its component chemical constituents[26].In order to remove surface moisture, the study's Teffstrawash sample was exposed to the sun and was burnt in a carbonate furnace for three hours at 750°C to get the essential BTSA. The ash particle size was then minimized to the appropriate level of finesse and sieved to remove impurities and coarser particles.The burning technique, burn duration, burn temperature, separation procedure, and grinding are the primary ash processing parameters that affect the chemical contents of Teffstraw ash (BTSA).The composition of the oxides SiO_2, Al_2O_3, and Fe_2O_3 is 70%or higher per the chemical specifications of ASTM C618.Table 1 contains the findings of the chemical analysis of the BTSA sample[25].Following the chemical study, SiO2, Al_2O_3, Fe_2O_3, and CaO are the main BTSA oxides, together with minor ignition loss (LOI)[25].

Teff straws' high silicon content is equivalent to that of other high-silica biomasses like rice husk and wheat husk[27][28]. Furthermore, the BTSA was found to have low alkali content like K_2O (7.84%) implying the lowvalue for an alkali-silica reaction when used in concrete, it would not cause the significant reduction for the strength of the concrete[29].As a result, it is basic to take BTSA aspozzolanic material due to the presence of the high amount of SiO_2, $Al2O_3$, and CaO.Teff straw can be an excellent source of high-quality silica[30].

Table 1: Major chemical compounds of BTSA[25].

Major oxides	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	LOI
percentage	74.92	2.05	0.62	5.06	7.84	0.01

2.1.3. Fine aggregate. The study's fine aggregate came from quarries close to Debre Tabor, Ethiopia. Aggregates less than 4.75 mm are classified as fine aggregate by ASTM C33.As a fine aggregate for this investigation, locally accessible well-graded river sand that is devoid of harmful elements is used. According to the ASTM standard, a number of tests are run to determine the fine aggregate's quality. As indicated in Table 2 and Figure 1, the sand utilized in the study possesses the following characteristics that are in compliance with ASTM criteria.

Table 2: Properties of sand

Tests conducted	Test result	Test method	Allowable limit	Standard
Fineness modulus	2.98	ASTM C136	2.3-3.1	ASTM C33
Unit weight	1316.67	ASTM C29	1200-1760kg/m3	ASTM C33
Specific gravity	2.68	ASTM C128	2.3-2.9	ASTM C128
Absorption	1.63	ASTM C128	0.2-2%	ASTM C128
Moisture content	2.3	ASTM C566	0-10%	ASTM C33
Silt content	3.67	ASTM C117	≤5%	ASTM C33

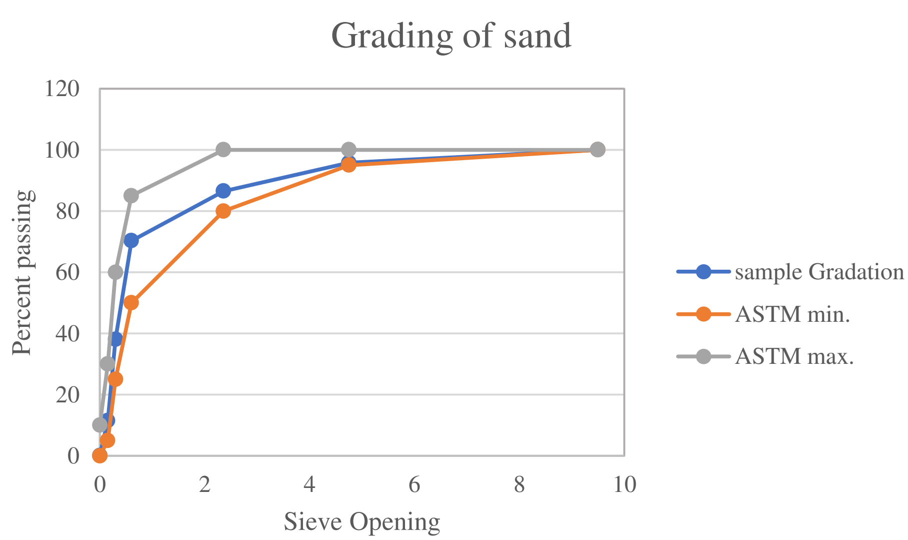

Figure 1: Grading of sand

2.1.4. Coarse aggregate. Well-graded crushed basaltic stone coarse aggregate that complies with ASTM criteria was utilized, and it was washed to remove dust and other harmful contaminants. The characteristics and gradation of coarse aggregate are displayed in Table 3 and Figure 2.

Table 3: Properties of coarse aggregate

Tests conducted	Test result	Test method	Allowable limit	Standard
Unit weight	1660	ASTM C29	1200-1760 kg/m^3	ASTM C33
Specific gravity	2.69	ASTM C128	2.3-2.9	ASTM C128
Absorption	1.96	ASTM C128	0.2-2%	ASTM C128
Moisture content	0.91	ASTM C566	0-10%	ASTM C33

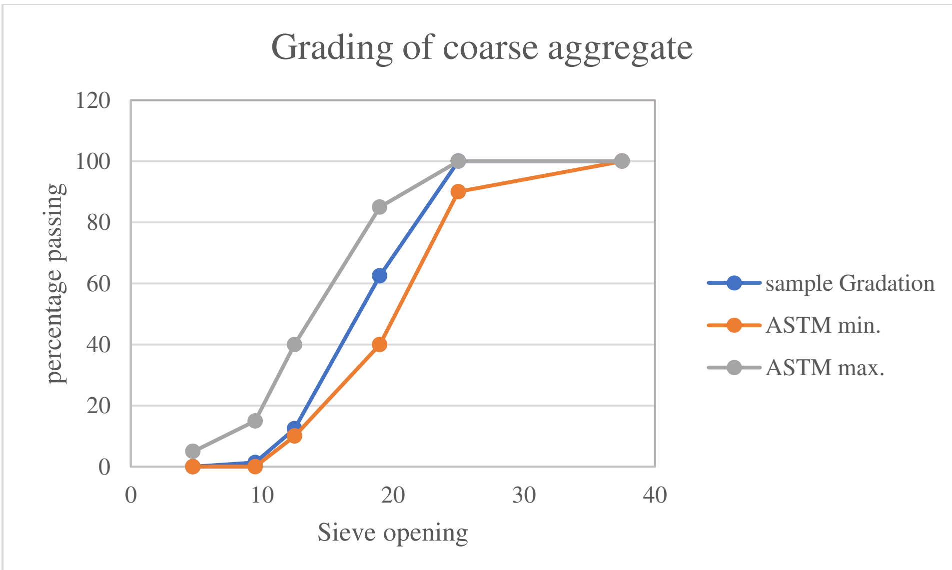

Figure 2: Grading of coarse aggregate

2.2. Mix Design

The study's concrete amounts and ratios were specified using the ACI 211.1 technique. Concrete having a 30 MPa compressive strength was used in the investigation. Five concrete mixtures, which were created through trial and error, were constructed for BTSA percentages ranging from 0% to 20% by weight of cement with 5% increments. All concrete mixtures had a slump range of 27–48 mm and a constant water–cement ratio of 0.5. Table 4 shows the reference concrete mix proportion.

Table 4: Reference concrete mix proportion

mix code	per	BTSA (kg)	Cement(kg)	Water (Lit)	Coarse aggregate(kg)	sand(kg)
BTSA-0%	m^3	0	380	190	996	779
	Trial	0	7.82	3.91	20.51	16.04

2.3. Test Methods

Prior to production, every material's engineering property that are required for describing the kind of materials used and attributes that can affect the manufacture of concrete were established. According to ASTM C-192, a pan concrete mixer was used to mix the constituents of concrete mixtures, which were all

weighed out in accordance with their proportions. Concrete was slump tested using a slump cone, which was fed straight into cube molds and compacted by hand for slumps under 50 mm. The concrete was then removed from the molds 24 hours after casting and placed in a curing tank.
The fresh properties of all concrete samples were used to determine the workability of the concrete after various tests were conducted on the materials qualities of cement, fine aggregates, coarse aggregates, and BTSA. The slump test with ASTM C143 was performed on a fresh concrete mix to evaluate the concrete's workability. Using ASTM C-187 and C-191, the consistency and setting times of BTSA and OPC were tested.
A total of 135 (150 mm *150 mm *150 mm) concrete cube specimens were constructed for the mechanical properties of concrete tests,45 cubical specimens (100 x 100 mm x 100 mm)were constructed for the water Absorption capacity of concrete, and 135 beam specimens (100 mm x 100 mm x 500 mm) were constructed for the Flexural strength of concrete. After being prepared, the samples were demolded and submerged in water for 24 hours to cure. Then, compressive strength, water Absorption, and Flexural strength tests were performed in accordance with ASTM C-109ASTM C-642and ASTM C-293respectivelyat various curing ages (7, 14, and 28 days).

3. Results and Discussion

3.1. BTSA on the Concrete Fresh Properties

3.1.1. Consistency. Figure 3 displays the typical consistencies of pastes containing BTSA. The control paste was a typical 27.69% consistency. In comparison to the control paste which is BTSA 0%, all of the pastes containing Brown Teff Straw Ash exhibit higher normal consistency. The normal consistency was within the ASTM C-187 range of 27% to 33% up to a replacement level of 15%, but at 20% replacement, it exceeded the maximum consistency, and a consistency of 35.38% was noted. In general, an increase in BTSA content was associated with an increase in the consistency of blended cement. This occurs because BTSA's presence increases the quantity of fine particles in the mixture, which raises the need for mixing water.

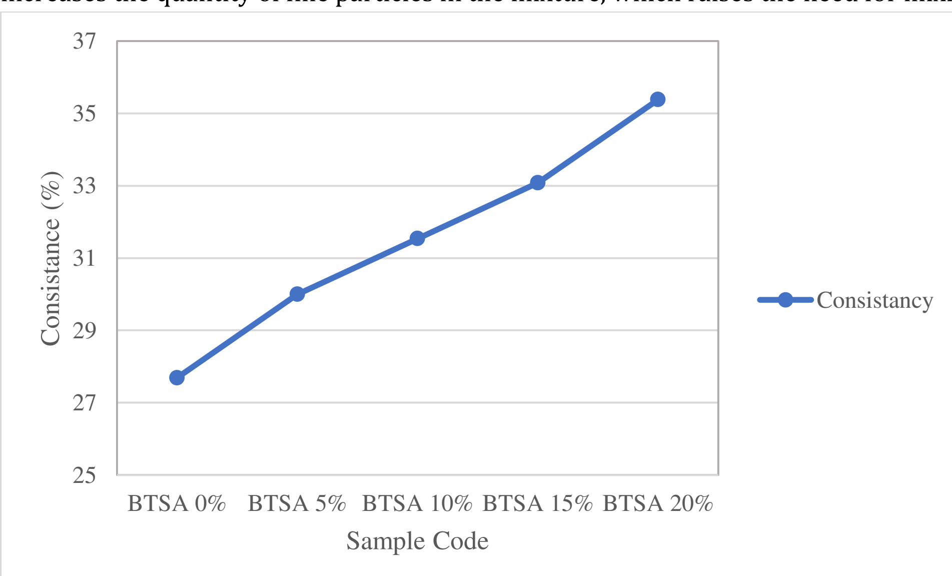

Figure 3: Normal consistency of blended paste containing BTSA

3.1.2. Setting Times. Figure 4 shows the initial and final setting times of mixes with various BTSA contents. The figure showed that the initial and final setting times, which fall within the ranges of ASTM C-191 and are, respectively, 62.5-110 minutes and 295-490 minutes, respectively. Due to the fact that primary cement hydration will be decreased with the reduction of cement content, the setting time of concrete generally showed a rising tendency with an increase in share of BTSA content. As BTSA has a much lower CaO content than cement, adding more of it greatly reduces the hydration of blended cement. As a result, BTSA will exhibit a secondary reaction, which eventually lengthens the time required for the blended cement to set. However, BTSA replacement can meet the blended mix's need for setting time up to a 20% level.

Figure 4: Initial and Final setting Time of pastes containing BTSA

3.1.3. Workability. Figure 5 displays an overview of the combinations' results from the slump test. The slump of the concrete, as depicted in the figure, ranged from 27 to 42 mm. Concrete slump in general exhibited a tendency to decline as BTSA content rose. This can be because BTSA increases the water requirement of the concrete mixture to make workable concrete because of its high specific surface area. In comparison to cement particles, BTSA particles are finer and have a larger surface area. With an increase in the amount of BTSA in the mixture, the water demand rises due to BTSA's water-absorbing properties [3].

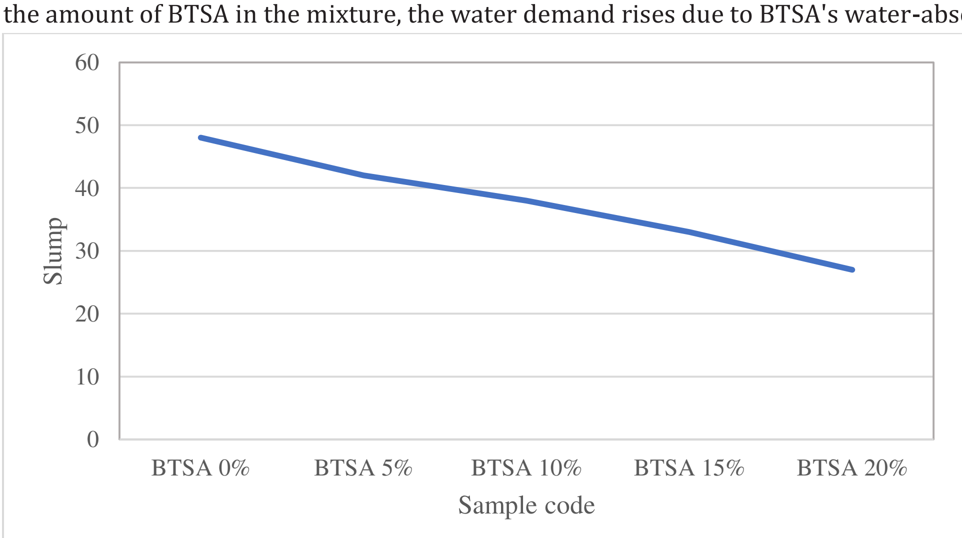

Figure 5: Slump test result

3.2. BTSA on the Concrete Mechanical Properties

3.2.1. Compressive Strength. Results for mixes' compressive strength are shown in Figure 6. The results for compressive strength indicated a falling trend with a rise in BTSA's share. This is as a result of BTSA having a much lower CaO content than cement. As a result, the mixture's CaO content will considerably drop as the BTSA share increases and the cement percentage decreases. The reduction in CaO in the blend of blended cements decreased the mechanical performance of concrete mixtures because CaO is crucial for the development of dignified CSH gel [26]. Although there was a tendency for compressive strength to decline as BTSA concentration increased, mixtures containing 5% and 10% BTSA reaches the design strength of concrete after 28 days of curing.

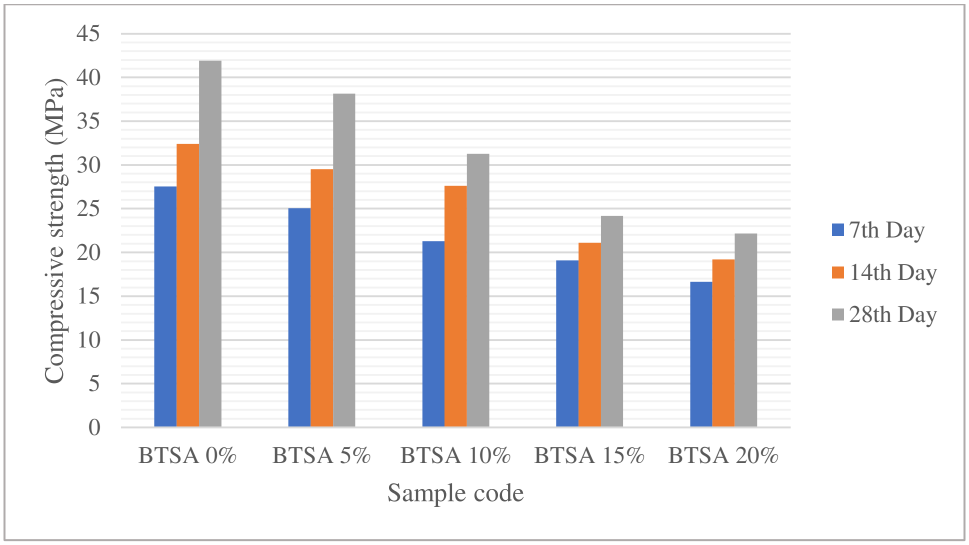

Figure 6: Compressive strength of concrete in different curing day

3.2.2 Flexural Strength. Results for mixes' flexural strength are shown in Figure 7. The results for flexural strength indicated a falling trend with a rise in BTSA's share. Although there was a tendency for flexural strength to decline as BTSA concentration increased, mixtures containing 5% and 10% BTSA reaches the design strength of concrete after 28 days of curing.

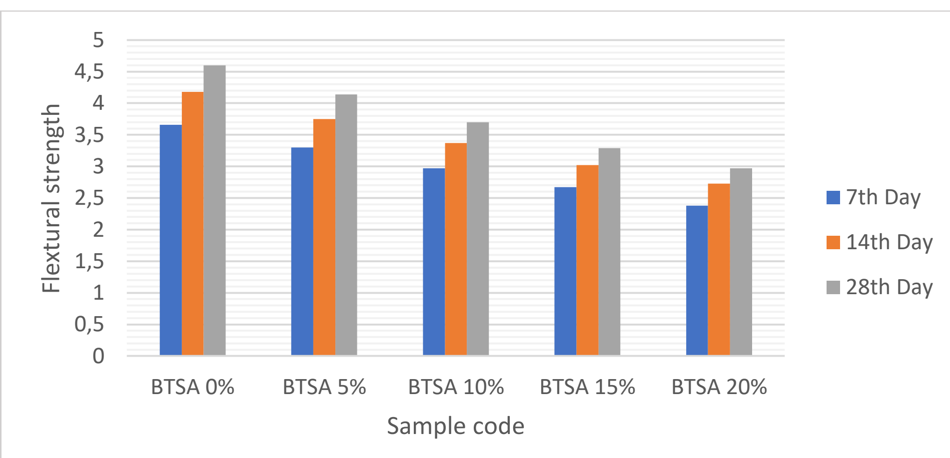

Figure 7: Flexural strength of concrete in different curing day

3.3. Water Absorption/Durability. Concrete's water absorption was examined in a laboratory setting using the ASTM C-140 standard. Figure 8 depicts the water absorption of various curing ages of concrete mixes. The water absorption of mixtures was measured between 7.25% and 15.06%. In general, the results of water absorption increased as the amount of BTSA content in the mixes grew, which is in good agreement with concrete's compressive strength. The densification of CSH gels, which finally results in fragmented and porous morphology, will be reduced by the increase in BTSA concentration. In the end, this causes mixes with increasing BTSA content to absorb more water [31].

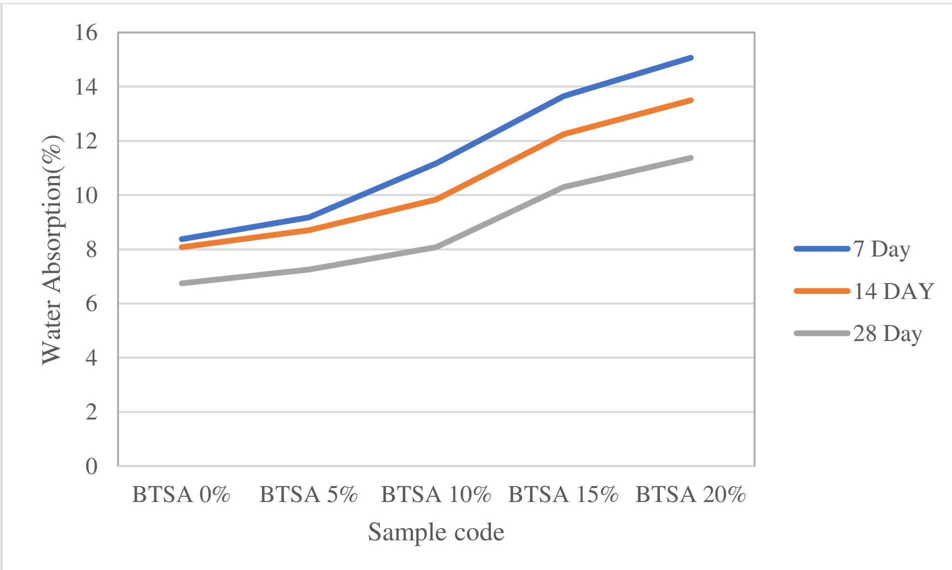

Figure 8: Water Absorption test result

3.4. Relationship between Compressive Strength and Water Absorption. A linear regression model was created to examine the relationship between the compressive strength and water absorption of BTSA concrete. Water absorption and compressive strength were inversely correlated, following the equations $y = -4.1634x + 67.943$ with an $R^2=0.9431$.

Figure 9 illustrates that as the number of curing day's increases, compressive strength increases while water absorption decreases. This is due to the fact that when concrete ages, it becomes denser and loses some of its ability to absorb water. Additionally, the relationship between compressive strength and water absorption is inverse, with the water absorption increasing as BTSA content increases. This is because the surface area increases as the amount of BTSA replacements increases[31].

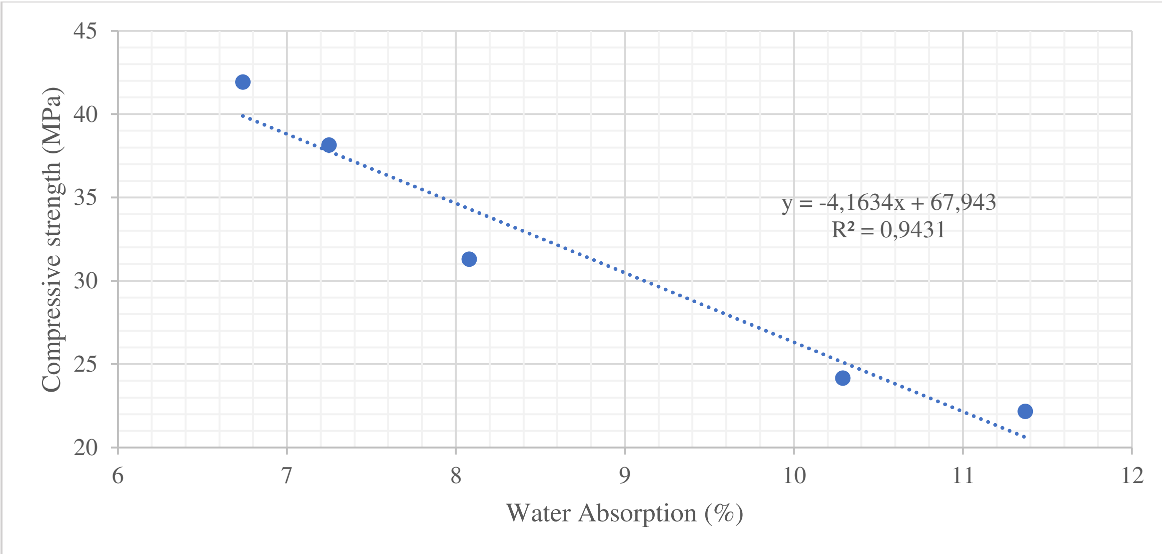

Figure 9: Relationship between compressive strength and water absorption

3.5. Relationship between Compressive Strength and Flexural Strength

A linear regression model was created to examine the relationship between the compressive strength and flexural strength of BTSA concrete. Compressive strength and flexural strength were directly correlated, following the equations y = 0.0753X –1.3655 with an R^2=0.9815.Figure 10 illustrates that as the number of curing day's increases, both compressive strength and flexural strength increases.

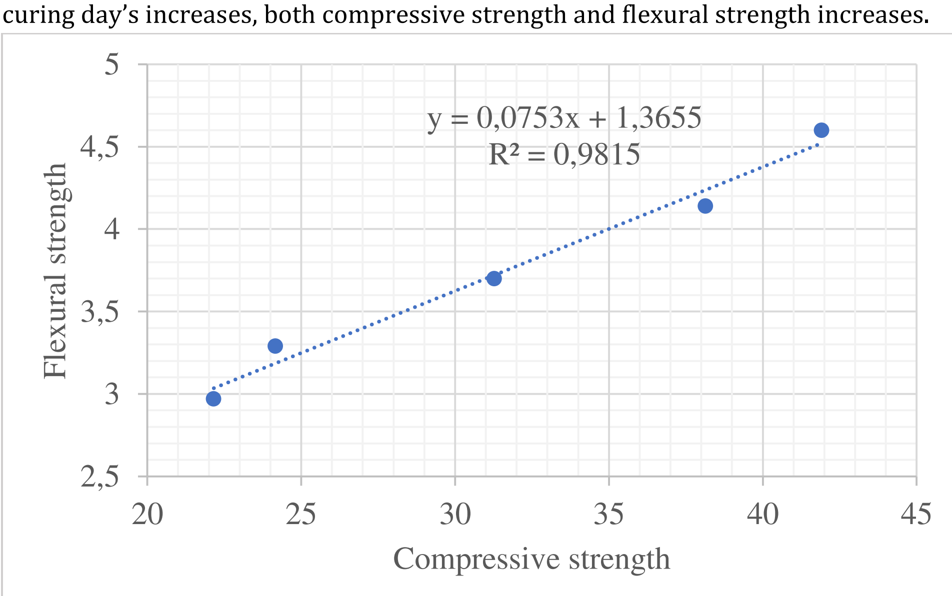

Figure 10: Relationship between compressive strength and Flexural strength

3.6. Relationship between Compressive Strength and Density

A linear regression model was created to examine the relationship between the compressive strength and Density of BTSA concrete. Density and compressive strength were directly correlated, following the equations y = 0.2001X - 457.25 with an R^2=0.9652.Figure 11 illustrates that as the number of curing day's increases, both compressive strength and density increases.

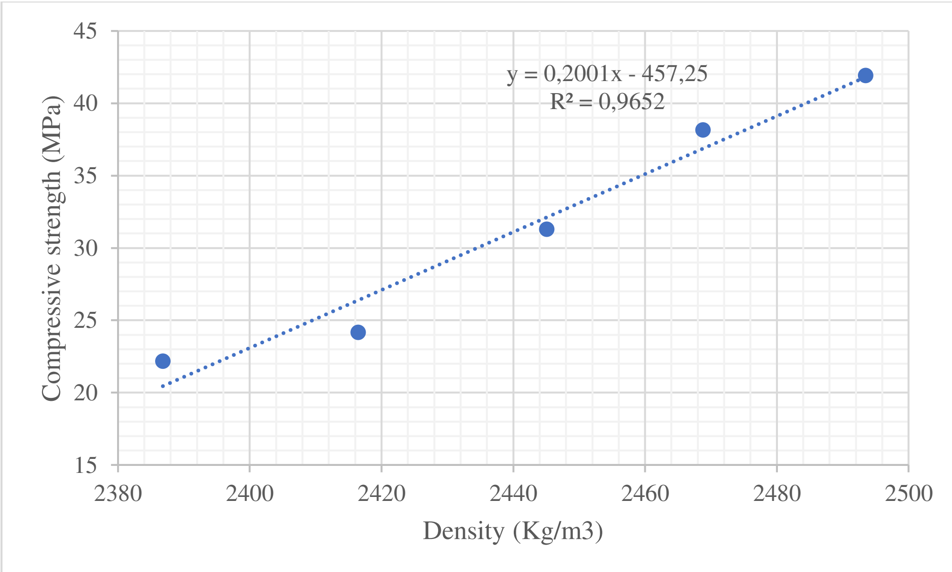

Figure 11: Relationship between compressive strength and Density

4. Conclusions

The following conclusions are drawn from the investigations about the use of Brown Teff Straw Ash (BTSA) as a replacement material for cement in concrete production:

- As the amount of BTSA in all samples rose, the workability of concrete decreased. However, concrete that was adequately workable was prepared up to the 20% BTSA replacement level.
- Concrete's compressive strength dropped as BTSA content rose. 5% BTSA and 10% BTSA mixes reach the designed strength of concrete after 28 days of curing, despite the fact that the compressive strength result showed a decreasing trend.
- As the BTSA content rises, water absorption rises as well, but it falls as the curing day rises.
- The flexural strength of concrete decreased with increasing BTSA content. Even though the flexural strength result showed a decreasing trend, 5% BTSA and 10% BTSA mixes meet the designed strength of concrete after 28 curing days.

In general, from the compressive strength point of view, the concrete made with BTSA has reached its design strength up to 10% cement replacement level. Therefore, BTSA has the potential to replace cement in the manufacturing of concrete up to 10% by weight, which would reduce the environmental impact of cement production.

The study also strongly encouraged future research into the long-term effects of concrete containing BTSA in order to identify any further significant durability characteristics of the concrete.

Data Availability

Data are available from the corresponding author upon request

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the research authorship and publication of this article.

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Authors' Contributions

Getachew Asefa Alene: conducted the experiment and drafted the manuscript.

Amare Tilahun Tessema: conducted the experiment and revised the manuscript.
Natnael Melsew Welelaw: supervised the experiment and revised the manuscript.

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