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REVIEW **Open Access**

Concrete Made with Partial Substitutions of Wheat Straw Ash: A Review

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Abstract

Many scientists are now focusing their attention on the utilization of valuable industrial or agricultural wastes as the primary raw material for the construction sector. These wastes, on the other hand, are affordable and readily accessible, making them ideal for commercial use while also contributing to the reduction of environmental degradation. Wheat straw ash (WTSA) is a kind of agricultural waste that has the potential to be utilized in concrete. Although many researchers are focused on utilization of WTSA in concrete. However, an updated review is required which provides easy access for the reader to get an idea about the benefits of WTSA in concrete. Therefore, this study provides a comprehensive review of the utilization of WTSA as a concrete ingredient. Physical and chemical compositions of WTSA, flowability, mechanical strength (compressive, flexure, tensile strength, and elastic modulus), and durability properties (permeability, carbonation, ultrasonic pulse velocity, alkali-silica reaction and chloride attacks) are the main aspects of this review. Results indicate that the performance of concrete improved with partial substitutions of cement with WTSA but simultaneously decreased the flowability of concrete. The optimum dose is important as higher dose results in decreased mechanical strength. The typical optimum dose ranges from 10 to 20% by weight of the binder. The performance of concrete in terms of durability was also improved but less research is carried out on the durability performance of concrete with WTSA. Additionally, despite WTSA's improvement in mechanical strength, concrete still exhibits lower tensile strain, which leads to brittle failure. Therefore, it was recommended that further study should be done to increase its tensile strength.

Keywords Eco-friendly concrete, Wheat straw ash, Mechanical strength, Durability, Scanning electronic microscopy

1 Introduction

In the engineering field, sustainable building has gained importance, and several perspectives have emerged to lessen the environmental effect of modern construction sectors (Alvee et al., 2022; Isler, 2012; Smirnova et al., 2021). The cement industry is challenged with issues such as cost increases in energy supply, as well as the need to reduce CO_2 ejections and the delivery of natural materials of better quality (Benhelal et al., 2013). From 1990, the worldwide output of cement is expected to increase steadily. Given that it is the second most consumed product on the earth after water. The business is expanding quickly, particularly in emerging nations like China and India where there is a huge need of cement for the construction of homes and other infrastructure (Nelson & Grayson, 2017).

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Fig. 1 shows that the worldwide production of cement is constantly increasing day by day due to fast-growing demands for infrastructure. Among the various developing countries, China contributes the maximum cement production (53%). Considering environmental concerns, building costs, raw material shortages, and increased energy consumption, the use of alternative materials is becoming a frequent issue throughout the world (Assefa & Dessalegn, 2019). Therefore, it is important to search alternative cementitious materials.

Utilizing byproducts as additional and alternative materials saves energy and reduces cement usage, lowering CO_2 emissions (Anwar, 2016; Dhir et al., 2009; Khan et al., 2017; Vigneshpandian et al., 2017; Vizcayno et al., 2010). Various industrial waste such as waste glass (Guo et al., 2021), marble (Amin et al., 2020), silica fume (Coppola, Cerulli, and Salvioni, 2004), fly ash (Kou & Poon, 2009), sewage sludge ash (Xia et al., 2023a, 2023b, 2023c) and waste foundry sand (Sua-Iam et al., 2019) have been successfully utilized in concrete. Furthermore, the addition of supplemental cementing materials in concrete might result in a considerable improvement in the strength and durability attributes of the concrete mix (Idir et al., 2010; Lee et al., 2018; Ling & Poon, 2013; Metwally, 2007). So extensive studies has been carried out on a variety of additives, such as rice husk, metakaolin, wastewater and palm shale oil, (Bheel et al., 2018; Cyr et al., 2007; Foong et al., 2015; Ling et al., 2011; Nizamuddin et al., 2019; Xia et al., 2023a, 2023b, 2023c). Besides the Utilization of industrial waste in concrete, agricultural waste is also a valuable option.

Wheat straw waste is a significant agricultural by-product generated from cereal production, and it contributes to environmental pollution when farmers burn it in open areas. However, when wheat straw waste is appropriately burned under regulated conditions, it produces a substance that possesses cementing qualities and may be utilized as a supplemental cementing ingredient in concrete (Mo et al., 2016). The successful use of waste in concrete will provide several advantages, including a more cost-effective solution for the building sector, decreased environmental and health hazards, and a favorable influence on the concrete overall durability (Abdelgader et al., 2019; Imbabi et al., 2012; Kim et al., 2017).

Wheat, along with sugarcane and rice, is the world's most important cereal crop, providing nutrition throughout the globe. According to research (Pan & Sano, 2005), One kilogram of wheat grain yields around 1.3–1.4 kg of wheat straw. The vast majority of wheat straw is utilized as the primary resource of nutrition for cattle and pigs (Kadam, Forrest, and Jacobson, 2000). However, it has been discovered in certain instances that burning wheat straws in an open field produces environmental pollution (smog) and health problems for the people who live in the surrounding region. Typically, 85 percent of this waste is burned in situ in the open air to prepare the lands for double-cropping or the future agricultural cycle (Montero et al., 2018). Furthermore, it has been reported that the burning of wheat straw results in the release of large amounts of toxic gases into the atmosphere, resulting in degradation of the air quality as shown in Fig. 2.

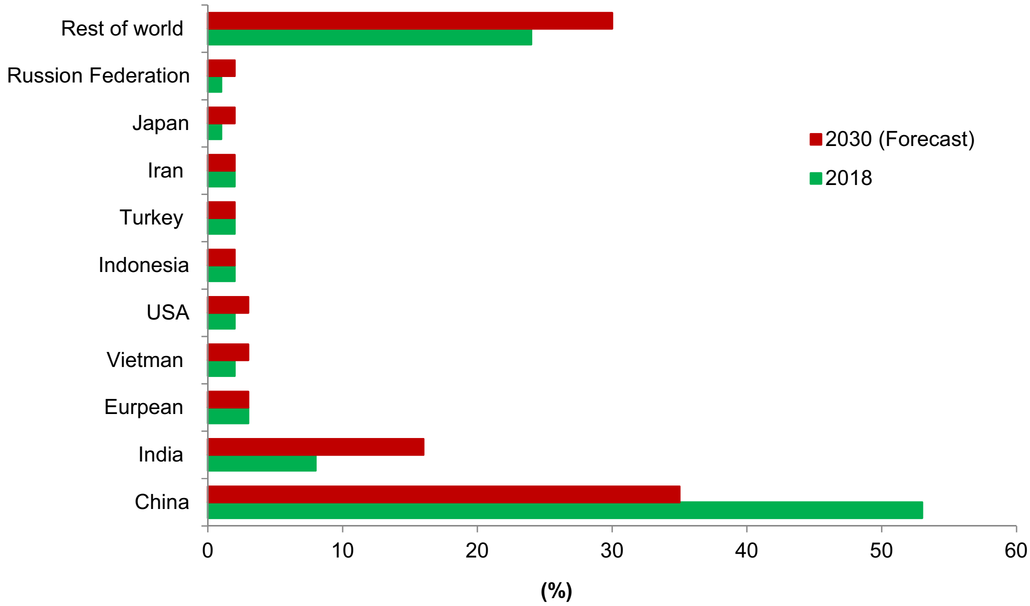

Fig. 1 Global cement supply 2018 and prediction 2030 (Association n.d.)

Fig. 2 Open burning of wheat straw which causes environmental pollution (Montero et al., 2018)

Numerous scholars investigated the efficacy of WTSA as a pozzolanic material and filler material in cement concrete (Ahmad et al., 2021; El-Sayed, Erfan, and Abd El-Naby, 2019). Due to the high siliceous content of WTSA, it may also be used as a binding material in concrete. Analyses of autoclave test samples using scanning electron microscopy revealed that pozzolan, which is derived from organic sources, contributes to the creation and manufacture of a variety of hydration products. The addition of WTSA to cement mortars increased the flexural and compressive strengths of the materials (Al-Akhras & Abu-Alfoul, 2002). In addition to its pozzolanic properties, WTSA also serves as a filler material that fills the voids among aggregates. The findings demonstrate that the filler effects of WTSA resulted in an improvement in the mechanical characteristics of mortar (Opeyemi, Otuaga, and Oluwasegunfunmi, 2014). Furthermore, the introduction of WTSA into cement composites increases the durability of the materials. Using WTSA in the percentage of some cement or sand, the absorption of cement composites reduced while acid and sulfate resistance increased (Khushnood et al., 2014). A similar increase in resistance to freeze-thaw damage was seen in concrete with WTSA. It was determined that the increased porosity and microstructure of WTSA-incorporated mortar and concrete were responsible for the better durability performance (Al-Akhras, 2011)

Brief literature shows that WTSA can be utilized as cement or as a fine aggregate substitute in concrete. However, the knowledge is scattered, and the reader feels difficult to judge the benefits of WTSA in concrete. Furthermore, according to the author's best knowledge, no recent comprehensive review on WTSA in concrete is available which is important to summarized the advantages and disadvantages of WTSA-based concrete. This review will offer multiple benefits for researchers such as the utilization of waste, decreasing cement consumption, the optimum dose of WTSA, strength as well as durability of concrete with WTSA, and points out the further research direction on WTSA in concrete to achieve maximum performance.

2 Physical and Chemical Composition WTSA

The estimated linear dimensions of wheat straw (which were acquired at random) range from 25 to 1.2 mm, with the largest value being 1.2 mm (Farooqi & Ali, 2019). The tensile, capacity, shear capacity, and density of WTSA, on the other hand, vary between 21.2 and 31.2 MPa, 4.91–7.26 MPa, and 865–871 kg/m^3, respectively, according to the results of the study (Aksoğan et al., 2016). The color of WTSA changes from brown to dark black as presented in Fig. 3. The gradation curve of WTSA is displayed in Fig. 4. It can be observed that the gradation curve of WTSA is well-graded with an S shape. The S shape gradation curve means that the aggregate contains different size of particle (small, medium, and large). The well-graded aggregate is important for better concrete performance such as workability, strength, and durability. The well graded aggregate posses less voids as the small size particle fill the voids present in larger size particles. The less voids result more workable concrete as more paste is accessible to decline the friction force among concrete ingredients. Similar less voids results more dense concrete with better strength and durability.

XRF analysis of WTSA revealed the following oxide composition, which is reported in Table 1. According to ASTM C618-15, the cumulative concentration of oxides of silica, alumina, and iron should be greater than 70 percent (Standard, 2015). The concentration of chemical oxides in WTSA (Jankovský et al., 2017) is greater than the limit defined by ASTM. Therefore, WTSA possesses binding properties and can be utilized as a binder to

Fig. 3 WTSA **a** before burning, **b** after burning (Memon et al., 2018)

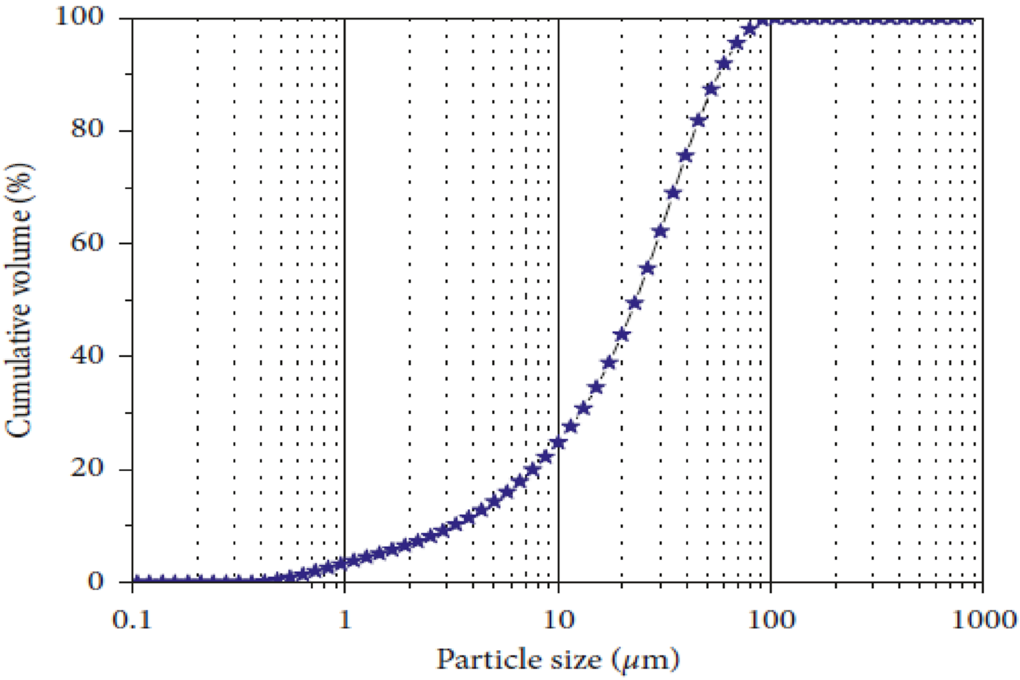

Fig. 4 Gradation Curve of WTSA (Qudoos, Ullah, and Baloch, 2019)

some extent. Furthermore, the WTSA samples have been shown to have more K_2O (Chandrasekhar et al., 2006) than the other ashes, which gives these ashes a dark grey appearance. The physical and chemical of WTSA composition have a greater impact on the strength and setting time of the paste. Particle size and surface area of WTSA play important role in chemical reaction. The rate of reaction increased with decreasing the particle size of pozzolanic materials. Similarly, the amorphous silica present in pozzolanic materials create secondary cementitious compound (CSH) by reacting with lime (form during hydration). The secondary cementitious improved the microstructure of concrete which result more strength and durability.

Fig. 5 depicts the X-ray diffraction (XRD) pattern of WTSA. The diffraction patterns of WTSA may be used to determine the presence of amorphous silica. Amorphous silica is preferred over crystalline silica because

Table 1 Chemical compounds in WTSA

References	Bheel, Ibrahim, et al. (2021)	Bheel, Ali, et al. (2021)	Ahmad et al. (2021)	Aksoğan et al. (2016)	Qudoos et al. (2019)
SiO_2	67.34	65.72	39.63	4.99	65.7
Al_2O_3	6.44	3.74	24.11	1.15	3.7
Fe_2O_3	4.36	2.59	6.2	0.95	2.6
MgO	–	2.69	3.5	4.63	2.7
CaO	10.60	7.85	12.56	25.44	7.8
Na_2O	0.47	2.46	0.049	1.28	2.5
K_2O	–	3.28	2.09	24.73	3.3

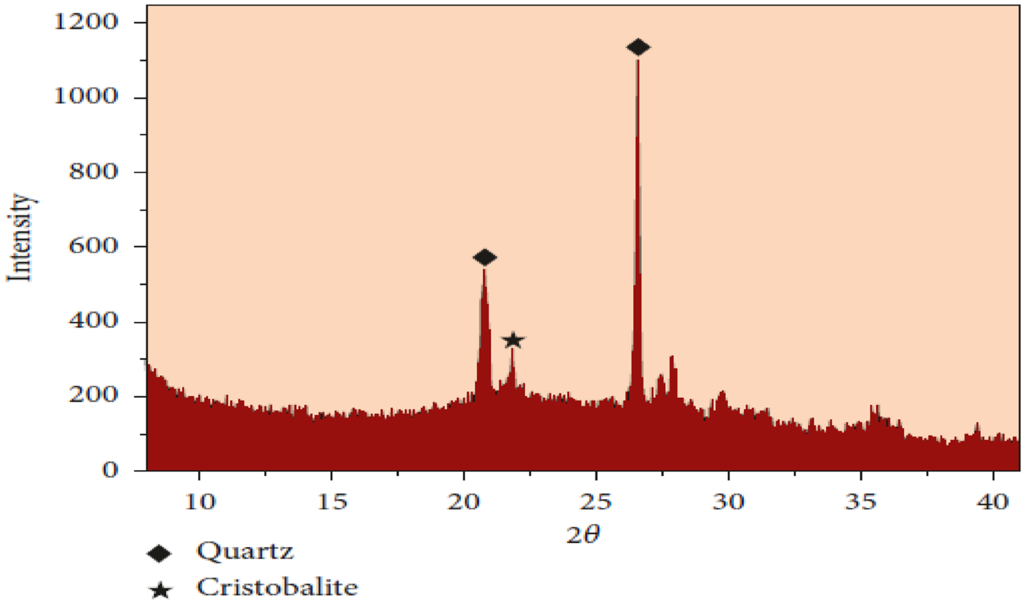

Fig. 5 XRD of WTSA (Qudoos et al., 2019)

it is more reactive, which accelerates the pozzolanic process (Jaques, Stehly, and Dunning, 1996). Therefore, the analysis of the WTSA compound demonstrated that a chemical contribution to strength growth may be expected after the introduction of the WTSA into the concrete mix.

Scanning electron microscope (SEM) cross-section and surface images were acquired to study the morphology of WTSA, as shown in Fig. 6. Fig. 6a shows a cross-section of the structure, revealing that the inner layers are composed of linked, thin-walled tubules, whereas Fig. 6b shows a similar structure but with smaller channels. Channels up to 10 mm in diameter may be found in the outer layers, which are denser and more compact than the inner layers, and channels up to 70 mm in diameter may be found in the inside layers. According to the surface SEM picture, the inner layers include many tiny surface holes with diameters of up to 5 mm, whereas the outer layers are formed of a relatively thick sheet and are lacking any surface pores. During the hydration process, more water was noticed in the pores, which had an undesirable influence on the flowability of the concrete. The lack of concrete flowability can cause more voids in concrete which results in lower strength and durability of concrete.

3 Fresh Properties

3.1 Slump Flow

Fig. 7 depicts the concrete slump flow with different substitution rates of WTSA. In the concrete samples, the findings showed that the slumps were 48, 36, 29, and 22 mm for 10, 20, 30, and 40% substitution of WTSA as a fine aggregate, respectively. These results of slump flow depict that the WTSA-based concrete possesses a lower slump value than those of the control concrete sample. The decrease in slump flow with the substitution of

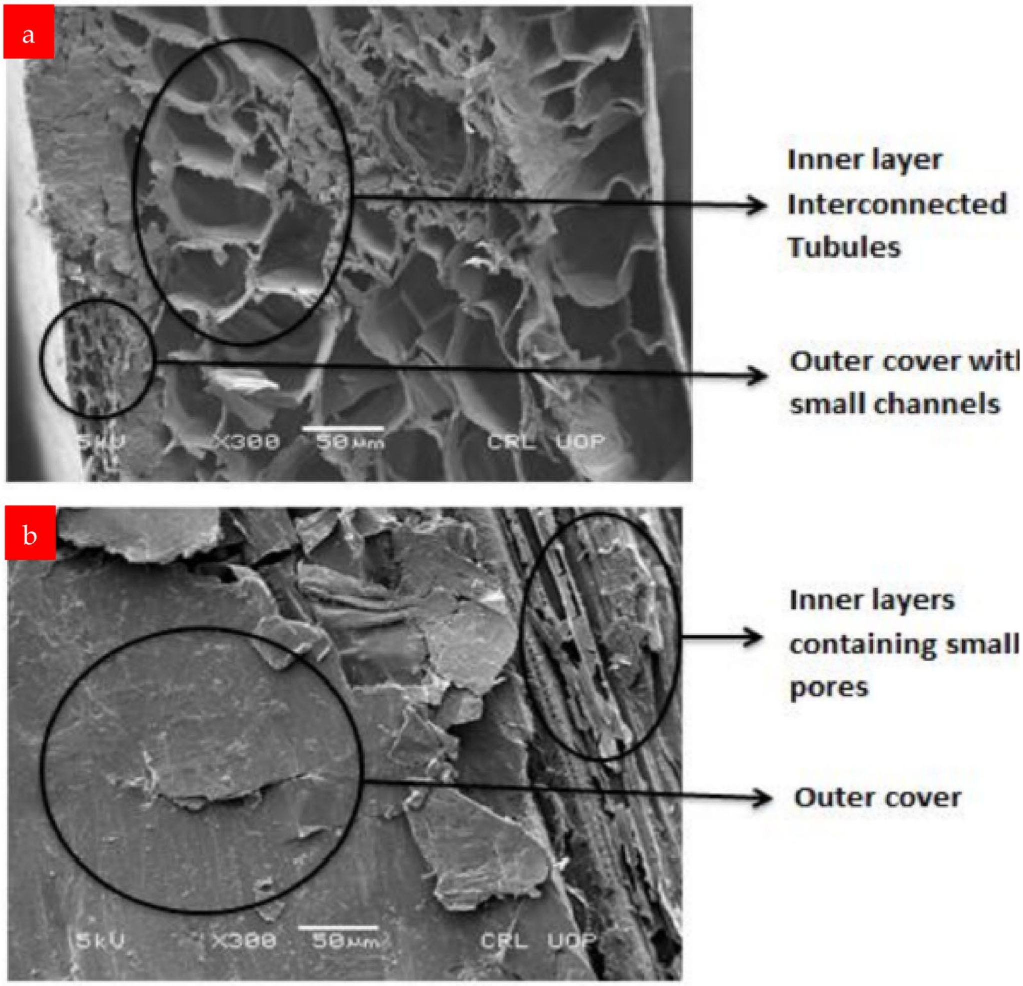

Fig. 6 SEM of WTSA (Memon et al., 2018), **a** cross section and **b** outer cover

WTSA is associated with its porous nature. The porous nature of WTSA causes more water absorption which causes a lower slump value.

A study also discovered that the flow of concrete decreases as the amount of WTSA used as a substitute for sand ingredients rises in the blend. This drop-in slump may be attributed to the enhanced surface area of WTSA which required more water than natural sand and caused a decrease in slump. This trend is comparable to that seen by Bheel, Ali, et al. (2021) who found that the fluidity of concrete reduced as the amount of WTSA in the concrete increased.

Similarly, the reduction in fluidity with the incorporation of WTSA can be credited to its shape and surface texture. The flaky, elongated, and rough surface of the WTSA particles which increase internal resistance between the concrete materials causes a decrease in flowability. Also, the larger surface area of WTSA increases the amount of water required for lubrication. It can be concluded that WTSA as a fine aggregate or as a cement can cause a decrease in concrete flowability. The decrease in flowability with WTSA can be associated with its porous nature, surface texture as well as flaky and elongated particle shape.

3.2 Fresh Density

Fig. 8 depicts the fresh density of concrete samples made with partial substitution WTSA as a fine aggregate. It can note that the fresh density of concrete decreased with the substitution of WTSA. The fresh density for 10, 20, 30, and 40% substitution of WTSA as a fine aggregate are 2280, 2200, 2140, and 2080 kg/m^3 correspondingly. A study showed that incorporating very high amounts of fly ash increases the air content and decreases the fresh density in concrete. However, this trend was not observed for low amounts of fly ash in concrete (Kurda et al., 2017). Furthermore, the density decreased because the ash was lighter than cement (Yang et al., 2016). Similarly, a study

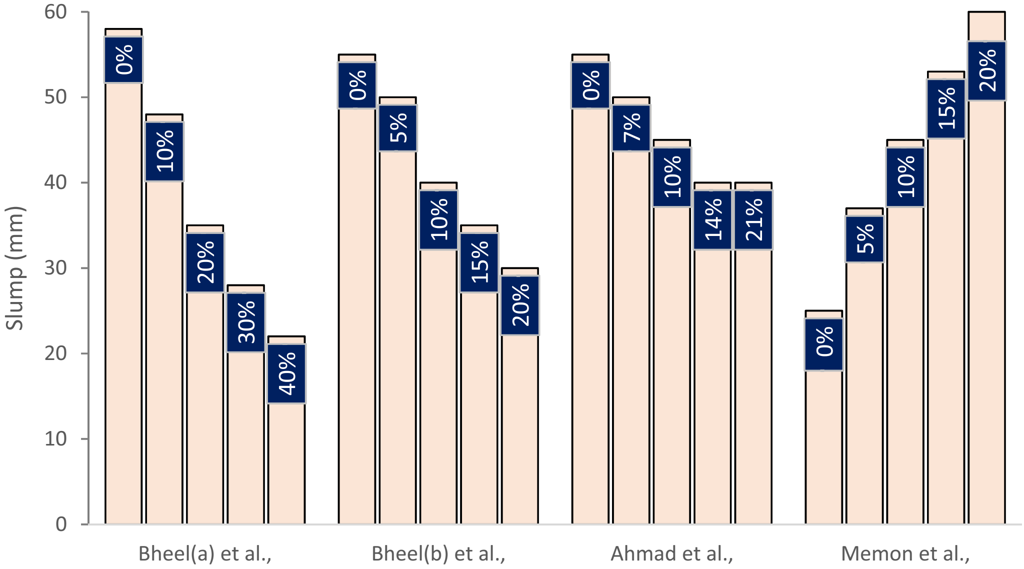

Fig. 7 Slump flow (Ahmad et al., 2019; Bheel (**a**), Ibrahim, et al., 2021; Bheel (**b**), Ali, et al. 2021; Moemon et al., 2021)

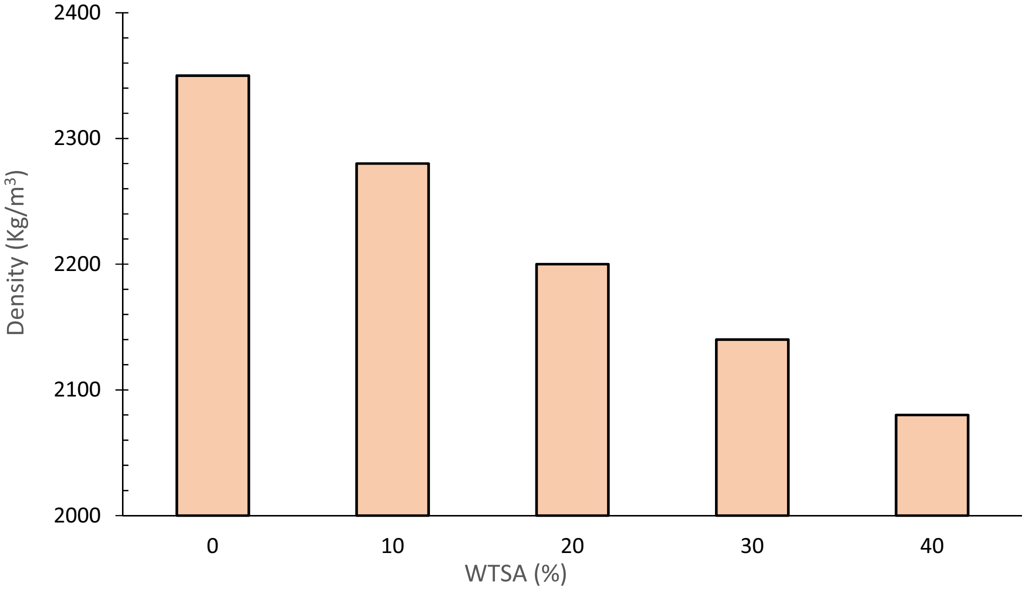

Fig. 8 Fresh density (Bheel, Ali, et al. 2021)

also concluded that the decrease in density with the substitution of WTSA is due to the smaller specific gravity of WTSA than that of the natural sand which results in a drop in density (Bheel, Ali, et al., 2021).

3.3 Setting Time (ST)

The ST of concrete is critical in determining the rate of strength growth. The impact of WTSA on the ST of various cement pastes is displayed in Fig. 9. It can be seen that ST increased with the increased proportion of WTSA.

A study also discovered that raising rice husk ash to a particular level increased ST. The greater surface area of rice husk promotes the nucleation effect of cement clinker, which accelerates the hydration kinetics of blended cement. The extension of setting time in blended cements incorporated with rice husk is due to the decrease in the relative content of cement clinker (Endale

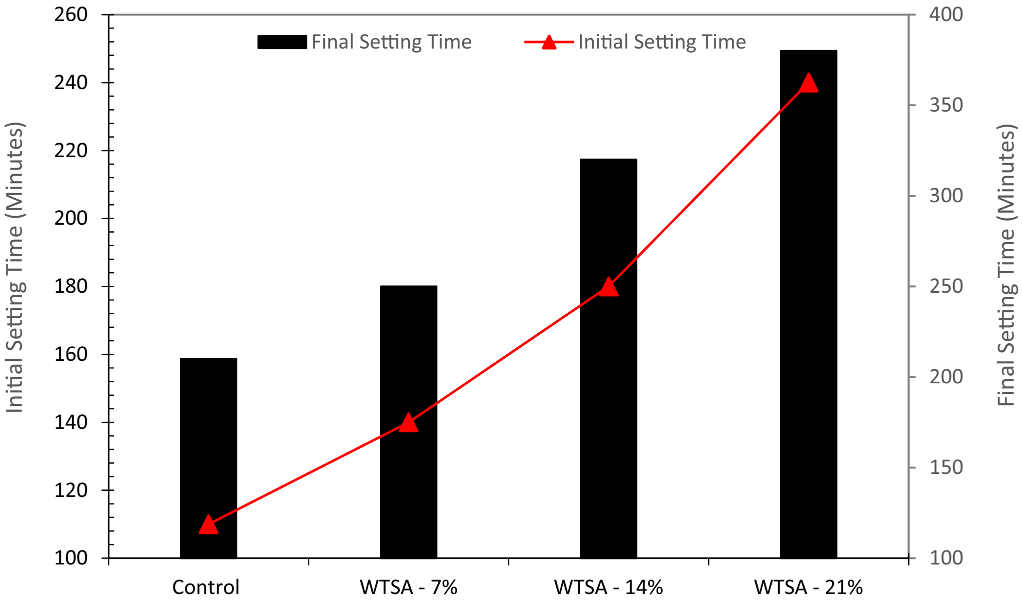

Fig. 9 Setting time (Ahmad et al., 2019)

et al., 2023). A study noted that the increasing percentage of WTSA from 0 to 21%, caused the initial and final ST of cement pastes to increase with time. The initial and final ST for the 21 percent WTSA were 233 and 391 min, respectively, which were 46.3 and 47.6 percent longer than the corresponding periods for the control group. The prolonged ST of cement pastes containing WTSA is due to the slower rate of reactivity with water (Ahmad et al., 2019). According to research, the ST of cement and the duration between the initial and final setting times increased with the substitution of silica fume. Consequently, using silica fume might dramatically and effectively delay the cement's setting time (Xu et al., 2020). It can be concluded that WTSA increased the concrete ST as the cementitious materials slow down the hydration reaction. Therefore, the concrete with the incorporation of WTSA can take more time to set and harden.

4 Mechanical Properties

4.1 Compressive Strength (CS)

The compressive strength (CS) of the mixtures was raised with the substitution of WTSA. However, a higher percentage of WTSA causes to decrease in the CS as indicated in Fig. 10 and Table 2. A study found that the concrete CS of mixtures incorporating WTSA as a 5 and 10 percent substitute of OPC is 8 and 12 percent higher than the CS of the control sample (Bheel, Ali, et al., 2021). It was shown that adding WTSA to a concrete mixture as a cement replacement increased CS by up to 20%. However, a study noted decrease in concrete CS with the further substitution of WTSA. The reduced CS shown in this study compared to the other study may be due to a higher water-to-cement ratio (i.e., 0.50) combined with the presence of coarse particles, which lowers the quantity of reference concrete per volume of concrete (Qudoos et al., 2018). Initially, the CS values of the mixes increased to a 10 percent incorporation of WTSA and subsequently dropped with further incorporation of WTSA due to lack of flowability. However, the CS values remained higher than those of the control concrete. When compared to the control mix, the 5, 10, 15 and 20% WTSA substituted mixes exhibited 19.66%, 39.06%, 15.69%, and 12.07% increase in CS, respectively. The 10% substitution of WTSA mix had the highest CS of all the concrete mixes tested at 90 days, with a highest value of 35.37 MPa.

It is thought that the enhanced value of CS is attributable to the pozzolanic potential of WTSA (Memon et al., 2021). The pozzolanic reaction of WTSA leads to the generation of additional hydration products (C–S–H gels), which refines the pore structure and promotes the strength development of blended cement(Al-Akhras & Abu-Alfoul, 2002; Biricik et al., 1999; Qudoos et al., 2018). WTSA concrete may continue to strengthen over time because of the additional binder created when silica interacts with readily available lime. The decrease in mechanical properties of blended cement with a high dosage of WTSA is due to the reduction in cement clinker content. Furthermore, compaction of concrete at a higher dose of WTSA is not impossible or required more energy due to lack of fluidity (Al-Akhras & Abu-Alfoul, 2002).

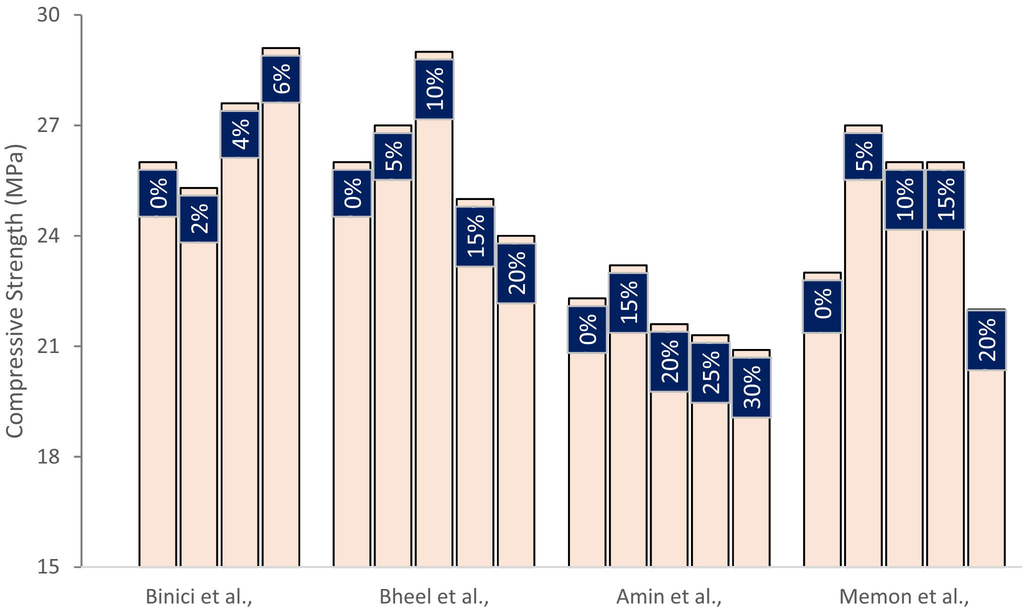

Fig. 10 Compressive strength (Amin et al., 2019; Bheel, Ibrahim, et al. 2021; Binici et al., 2008; Memon et al., 2021)

According to one research, finer ground ash resulted in a more intense pozzolanic reaction and properly filled the voids, causing an increase in the CS. The finer the particle size increased the reactivity of WTSA. A study also noted that grinding natural sand with a smaller particle size resulted in increased CS owing to an increased filler action (Qudoos et al., 2018). Furthermore, a study noted that the coarser WTSA particles have a reduced surface area, the nucleation procedure is slowed and the matrix's mechanical capacity is reduced (Xu et al., 2015). Therefore, the particle size of WTSA is an important role in concrete strength properties.

The early-age CS containing 15 percent and 20 percent WTSA was comparable to that of control mortar, and the CS containing 15 percent WTSA rise steadily with aging over time. It is due to the fact the pozzolanic action of WTSA gains strength with time. A study also noted that the rate of reaction of pozzolanic materials is much slower as compared to cement (Çelik et al., 2022). Similarly, a researcher discovered that the strength enhancement in 15 percent WTSA was 3 and 4 percent greater than that in the reference sample, respectively at the ages of 28 and 91 days. Furthermore, the mortars with substantially larger percentages of WTSA (25 percent and 30 percent) displayed the strength of the mortars declined as the proportion of WTSA increased to or above 20 percent. In addition, the results of the porosity tests showed that the porosity of the control mortar or mortar containing 15 to 20 percent WTSA significantly increased when compared to the control mortar.

4.2 Split Tensile Strength (SP)

A positive relationship between WTSA concentration and split tensile strength (SPS) of concrete mixes was observed as presented in Fig. 11 and Table 2. It can be concluded that the SPS of the concrete mixture increased up to 10% substitution of WTSA at all ages before it began to decline. Concrete mixes including 10% WTSA as a substitute for cement show 11 percent more SPS than that of the control mixtures. The increase in SPS may be related to the pozzolanic reaction of WTSA in which amorphous silica present in WTSA may interact with the calcium hydroxide (CH) in the concrete pore solution to produce more cementitious products. According to the researchers, these results are very comparable to those of earlier investigations where it was shown that adding 10% to 15% rice husk ash to concrete increased its SPS (Foong et al., 2015). Incorporating a larger concentration of WTSA, on the other hand, had an adverse diluting impact on the cement, resulting in a restricted supply of calcium hydroxide for the synthesis of hydration products.

A concrete blend with 30% WTSA shows the maximum SPS which is 3.45 MPa and the lowest SPS is 3.12 MPa after 28 days. In concrete with 40% WTSA, the minimum SPS is 3.3 MPa after 28 days. With the addition of WTSA up to 30%, it has been observed that the SPS increases because the surface area of WTSA is greater than that of sand. However, after the addition of WTSA beyond 30%, the SPS decreases, although the result is still greater than the result obtained with control concrete.

Table 2 Summary of fresh and mechanical performance of concrete with wheat straw ash (WTSA)

References	WTSA (cement or aggregate)	Type of blend	WTSA substitution range	W/C	Optimum (WTSA)	Slump	Compression strength (MPa) 0 to optimum (WTSA)	Flexure strength (MPa) 0 to optimum (WTSA)	Split tensile strength (MPa) 0 to optimum (WTSA)	Conclusions
Bheel, Ibrahim, et al. (2021)	Cement	Conventional concrete	0–20%	0.50	10%	Decline	26–29	5.2–6.0	3.0–3.5	Slump delined and strength improved
Bheel, Ali, et al. (2021)	Fine aggregate	Conventional concrete	0–40%	0.55	30%	Decline	30.0–33.0	4.5–5.1	3.1–3.45	Slump delined and strength improved
Qudoos et al. (2020)	Cement	Composites	0–20 g	0.40	20 g	–	60–70	9–9.2	–	Strength improved
El-Sayed, Erfan, and Abd El-Naby (2017)	Cement	Conventional concrete	0–20%	0.50	15%	Decline	37.7–41.5	–	–	Slump delined and strength improved
Ahmad et al. (2021)	Cement	Self compacting concrete	0–20%	0.45	10%	Decline	27–32	–	3.4–4.0	Slump delined and strength improved
Ahmad et al. (2019)	Cement	Conventional concrete	0–21%	0.49	14%	Decline	27–30	5.0–6.0	–	Slump delined and strength improved
Binici et al. (2008)	Fine aggregate	Conventional concrete	0–6%	–	6%	Decline	26–29	–	-	Slump delined and strength improved
El-Sayed et al. (2019)	Cement	Mortar	0–20%	0.45	15%	–	50–63	–	4.25–5.36	Strength improved
Qudoos et al. (2018)	Cement	Composites	0–30%	0.40	20%	–	63–67	–	–	Strength improved
Memon et al. (2021)	Fine aggregate	Conventional concrete	0–20%	0.50	5%	Increase	23–27	–	–	Slump increased
Amin et al. (2019)	Cement	Conventional concrete	0–30%	0.48	15%	–	22.3–23.2	–	–	Strength improved

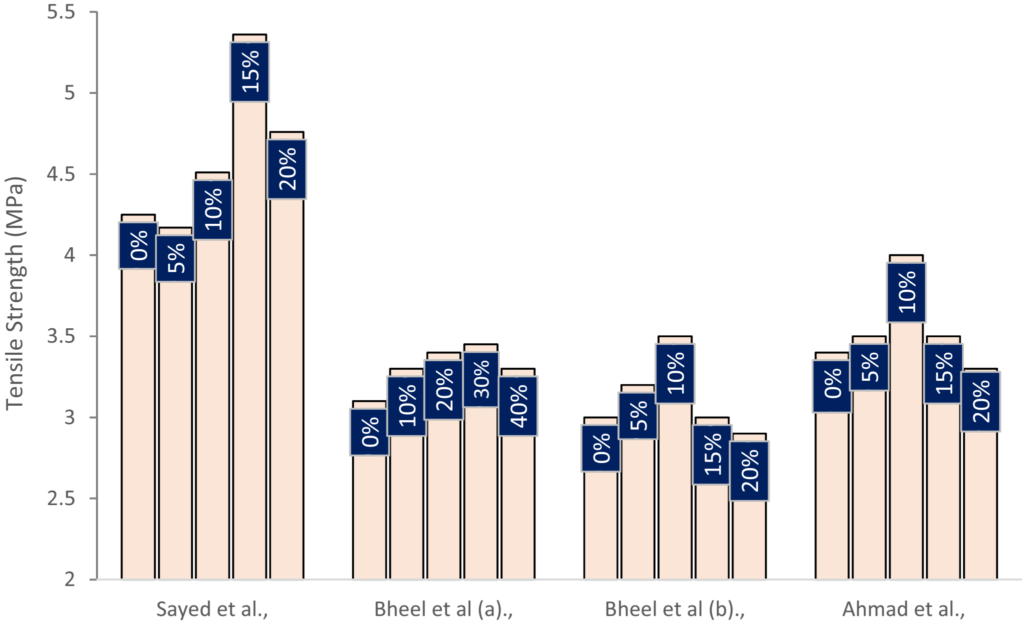

Fig. 11 Tensile strength (Ahmad et al., 2021; Bheel, Ali, et al. 2021; Bheel, Ibrahim, et al., 2021; El-Sayed et al., 2019)

similar to this, a study conducted by (Keerio et al., 2020) in which the mechanical capacity of concrete is improved by increasing the amounts of WTSA used as a substitute for fine aggregate in the concrete after 28 days up to 30 percent. The testing results revealed that the compressive, tensile, and flexural capacity improved by 32.8, 3.80, and 5.30 MPa, respectively when 0.50 percent of jute fiber was used in combination with 30 percent of WTSA at 28 days (Bheel, Ali, et al. 2021). Furthermore, a similar researcher claimed that the introduction of WTSA enhanced the SPS (Al-Akhras & Abu-Alfoul, 2002). When comparing the SPS of WTSA with that of the reference sample, the highest value was found at a 10 percent dose of WTSA. However, the SPS was lowered when the dose was increased by over 10%. Although the compaction process becomes more difficult at larger dosages (WTSA-20) owing to an absence of flowability which leads to more voids and lesser mechanical capacity (Ahmad et al., 2021).

The relationship between CS and SPS is seen in Fig. 12. From Fig. 12, it can be seen that there is a strong connection between these two characteristics, with an R square value larger than 90 percent. When one of the unknowns (either CS or SPS) is known, the equation shown in Fig. 12 will help to predict the SPS or CS of WTSA-based concrete.

4.3 Flexure Strength (FL)

A relationship between WTSA concentration and flexural strength (FL) of concrete is presented in Fig. 13 and Table 2. When WTSA was substituted up to a 30 percent concentration, the FL of the blend was raised as compared to the reference concrete (Bheel, Ali, et al., 2021). Additionally, the FL of all combinations increased with age, proving that, except for mixes containing 40% WTSA, the addition of WTSA to concrete mixtures had no adverse effects on the progression of the hydration response with time. However, according to the study (Ahmad et al., 2019), 14% substitution of WTSA as cement results in maximum FL as shown in Fig. 13. It can be observed that there was a significantly decrease in the FL of concrete mixes containing 20% WTSA (Bheel, Ibrahim, et al., 2021).

In this case, the diluting impact of the WTSA on the cement results in a lack of refinement of the interfacial transition zone and a subsequent influence on the long-term FL of the material (Bheel, Ibrahim, et al., 2021). The study also noted that the addition of WTSA to cement mortars increased the FL and CS (Al-Akhras & Abu-Alfoul, 2002) due pozzolanic and micro-filling action of WTSA.

In addition to its pozzolanic properties, WTSA also serves as a filler material that fills the gaps among concrete materials. The findings demonstrate that the filler effects of WTSA resulted in an improvement in the mechanical characteristics of mortar (Opeyemi et al., 2014). Upon 28 days of testing, the CS and FL of a concrete mixture containing 14 percent WTSA were 7.5 percent and 19.5 percent higher than those of control mixtures, respectively (Ahmad et al., 2019). Depending

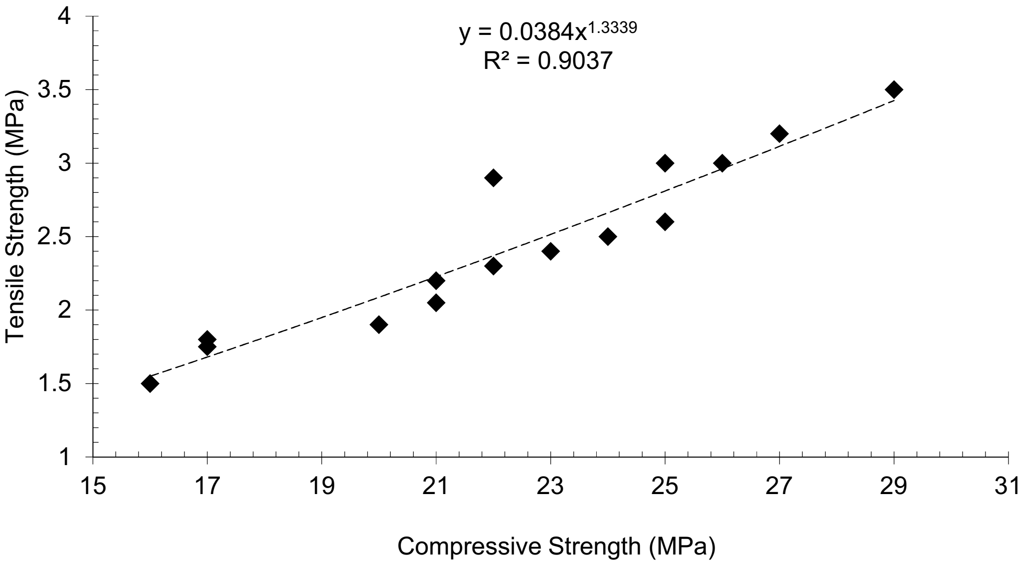

Fig. 12 Correlation between tensile and compressive strength: data source (Bheel, Ibrahim, et al. 2021)

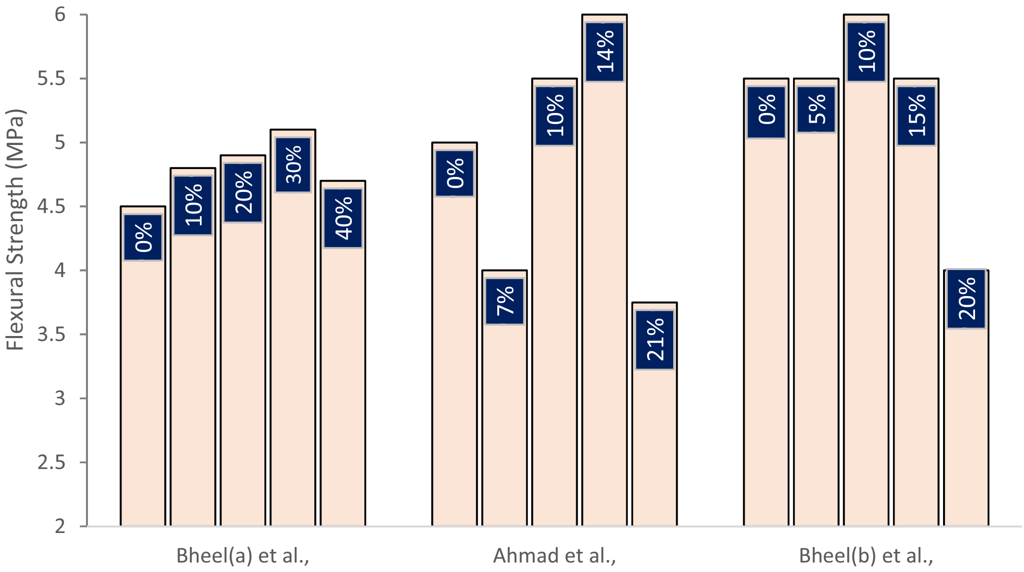

Fig. 13 Flexural strength (Ahmad et al., 2019; Bheel, Ali, et al., 2021; Bheel, Ibrahim, et al., 2021)

on the substitution ratio of WTSA, FL ranged from 4.65 MPa (40% WTSA) to 5.05 MPa (30% WTSA). All mixes of WTSA show strength higher than the control sample. It has been discovered that increasing FL by up to 30 percent with WTSA results in improved FL, with a minor drop with 40 percent of WTSA (Bheel, Ali, et al., 2021).

Increased FL of all concrete mixes was shown to be related to the curing time of concrete samples. The FL of a concrete mixture containing 14 percent WTSA (C14 percent WTSA) at 28 days was shown to be the greatest when compared to all other WTSA substation ratios and control concrete. However, due to the high rate of hydration at an early age, the control combination without WTSA (0 percent WTSA) exhibited greater FL after 7 days of hydration than the WTSA concrete mixture (14 percent WTSA). Furthermore, the behavior of the increase in FL was comparable to that of the increase in CS (Ahmad et al., 2019).

Fig. 14 depicts a relationship between FL and CS of the concrete with various substitution ratios of WTSA. It can be observed that the concrete mechanical

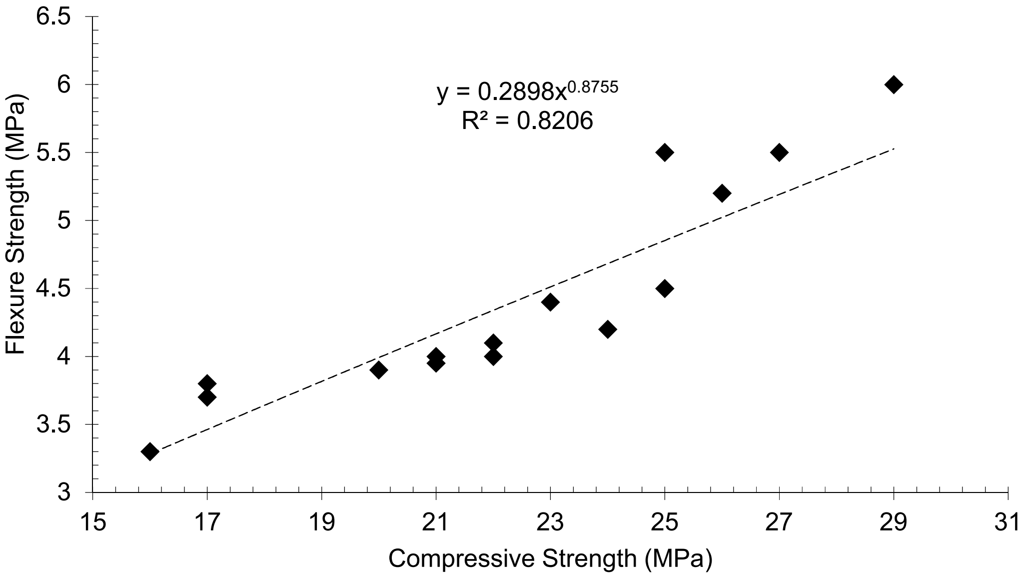

Fig. 14 Correlation between tensile and compressive strength: data source (Bheel, Ibrahim, et al., 2021)

characteristics (compressive and flexural strength) have a good linear connection with one another, as shown in Fig. 14. The regression line appeared to be straight with the R square value of 82%. Therefore, it will be possible to predict the FL of concrete mixes from CS that include WTSA using the equations shown in Fig. 14.

4.4 Modulus of Elasticity (ME)

The stiffness or resistance to deformation of a concrete structure is measured by the ME of concrete. The ME of the concrete mixes is shown in Fig. 15 at various substitution ratios of WTSA and curing ages. The ME of all concrete mixtures increases when the concrete curing ages and the WTSA substitution ratio to the mix increases (up to 20%). The increase in the ME of the concrete mixtures

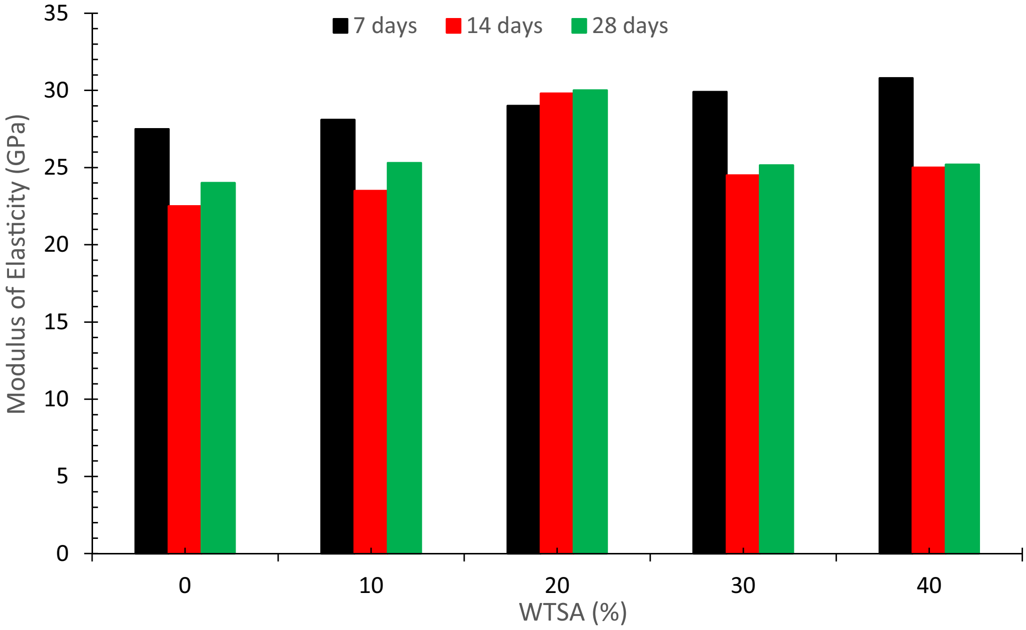

Fig. 15 Modulus of elasticity (Bheel, Ibrahim, et al., 2021)

with age may be attributed to the continual hydration and pozzolanic reaction of the binders in the concrete mixtures. Contrarily, the increase in ME with increasing WTSA concentration may be explained by the probable pore refinement that results from the integration of WTSA, strengthening the interfacial link between the aggregate and the binder matrix. An improvement in ME performance was achieved by a combination of the pozzolanic reaction, which increased binding properties, and the micro-filling effect of WTSA, which produces more dense concrete. Improved interfacial transition zone caused by the substitution of WTSA results in increased concrete ME (Ramezanianpour, Mahdikhani, and Ahmadibeni, 2009). A stronger interfacial connection between the aggregate and the OPC in the matrix increased the concrete ME. However, the authors observed that fewer researchers considered ME in their studies. Therefore, the review recommends more details studies related to ME of WTSA based concrete.

Finally, the present review concludes that WTSA may be used to replace 10–20 percent can be utilized in concrete either as cement replacement or as a fine aggregate, resulting in strength that is equivalent to or better than the control sample. The improvement in strength due to substitution WTSA can be related to the pozzolanic reaction and filler capability of WTSA particles

5 Durability

5.1 Permeability

The water or harmful acid can easily enter the concrete structure with permeable voids which cause less durable concrete. The permeability of concrete with and without the substitution of WTSA in different percentages is shown in Fig. 16. Permeability of samples at 40% to 10% substitution of WTSA ranges from 14.0 mm (40% WTSA) to 22.0 mm (10% WTSA) which is lower than that of the reference sample. It is observed that the permeability of the concrete reduces as the amount of WTSA in the concrete increases. According to research, adding fly ash to concrete decreases the permeability void volume by 6–11% when compared to concrete that does not include fly ash (Supit & Shaikh, 2015). Additionally, a study (Shaikh & Supit, 2015) studied how varied fly ash contents in concretes affected permeability voids. The permeability void of concrete was shown to diminish at a fly ash replacement rate of 40%, but at a level of 60% replacement, it was larger than in reference samples. On the other hand, according to (Mardani-Aghabaglou et al., 2013), fly ash concrete had more permeability voids compared with the reference sample, and the amount of voids enhance as the fly ash proportion increased. Due to the fact that WTSA absorbs more water than the fine aggregate. The water evaporates later which leaves empty cavities, leading to more permeability. However, the study noted (Xu et al., 1995) that as the doses of metakaolin as cement components in concrete increase, the permeability of the concrete decreased. The decrease in permeability depth with the substitution WTSA is due to the pozzolanic activity of WTSA which improved the interfacial transition zone (ITZ), leading to fewer cracks which result in less permeability of water into concrete. Also filling voids of WTSA results decrease in permeability depth. A study also noted that the blends densification, $Ca(OH)_2$ concentration decrease, and cement

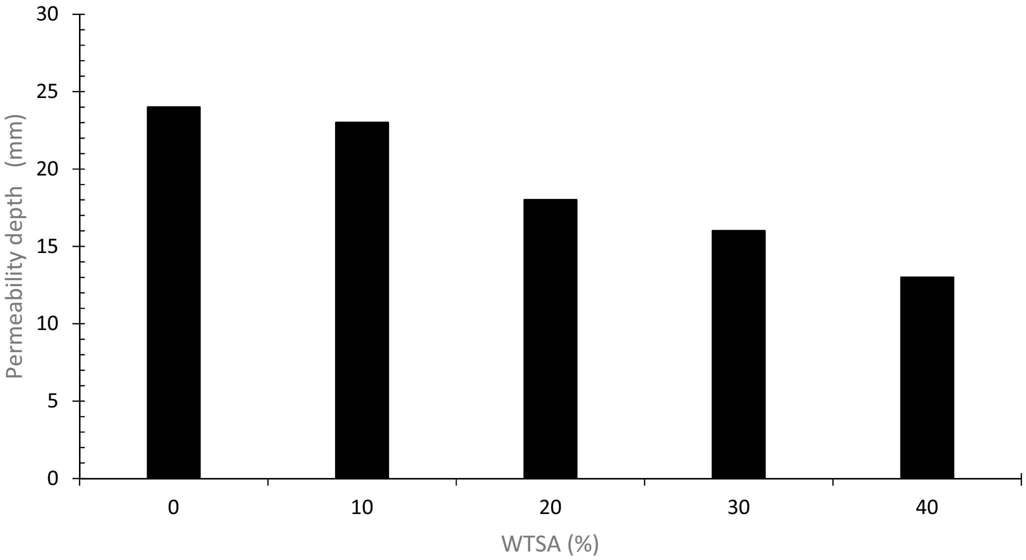

Fig. 16 Permeability (Bheel, Ali, et al., 2021)

paste-aggregate interface refinements are the causes of the larger permeability reductions with silica fume. The pozzolanic interaction between silica fume and calcium hydroxide causes a progressive densification of the transition interfacial zone throughout the hydration (Song et al., 2010).

5.2 Carbonation Depth

Carbonation is the chemical reaction between carbon dioxide present in the air with the calcium hydroxide form during the hydration process which results in calcium carbonate. The carbonation reaction decreased the alkalinity of concrete. The decrease in alkalinity results in corrosion to the steel reinforcement, leading to less durable concrete. A total of 14.12 mm of carbonation depth was noted when WTSA was replaced with 0% (control), while fiber additions of 0.5, 1%, and 2% resulted in carbonation depths of 13.4, 13.5, 13.85, and 14.12 mm. On the other hand, samples that had undergone WTSA treatment exhibited decreased carbonation depth. For instance, with a 20% replacement of WTSA with 0%, 0.50%, 1%, and 2% fibers, respectively, carbonation depths of 12.29, 12.55, 12.92, and 13.11 mm were recorded. In contrast to their equal 0% WTSA specimens, the carbonation depths of these samples decreased by 8.3%, 7.5%, 6.7%, and 7.2%, respectively. Due to the pores' increased internal conectivity because of the fibers' insertion, the pulse velocity has decreased. This may be the cause of the higher carbonation depths seen in the fiber-reinforced specimens (Qudoos et al., 2019). It was discovered that adding WTSA increased the performance of fiber-reinforced cement composites. The pozzolanic process, which consumes calcium hydroxide and produces a denser microstructure, as well as the filler characteristics of WTSA may be partly responsible for this improvement. In addition, the WTSA particles' small size served as nucleation sites for the creation of additional hydration products, which enhanced the microstructure of the composites (Qudoos et al., 2018).

5.3 Ultrasonic Pulse Velocity (UPV)

Depending on their size, the ashes were ground in a laboratory ball mill for 30, 60, and 120 min (G30, G60, and G120). In place of cement, WTSA was employed in percentages of 20%, 30%, and 40%, respectively (by weight). Following 7, 28, and 90 days of curing, the mortar samples were subjected to an ultrasonic pulse velocity test and the results are demonstrated in Fig. 17. The results of the research demonstrate that the UPV improved with enhancing curing days. At 7, 28, and 90 days, the reference sample's UPV values were 3.7, 4.05, and 4.18 km/s, respectively. This is mostly caused by the cement's ongoing hydration over time, which creates a denser microstructure. Due to the dense microstructure, cementitious composites have a greater UPV (Koksal, Gencel, and Kaya, 2015).

The addition of WTSA particles also resulted in a large rise in the UPV, and this increase was noticeably more

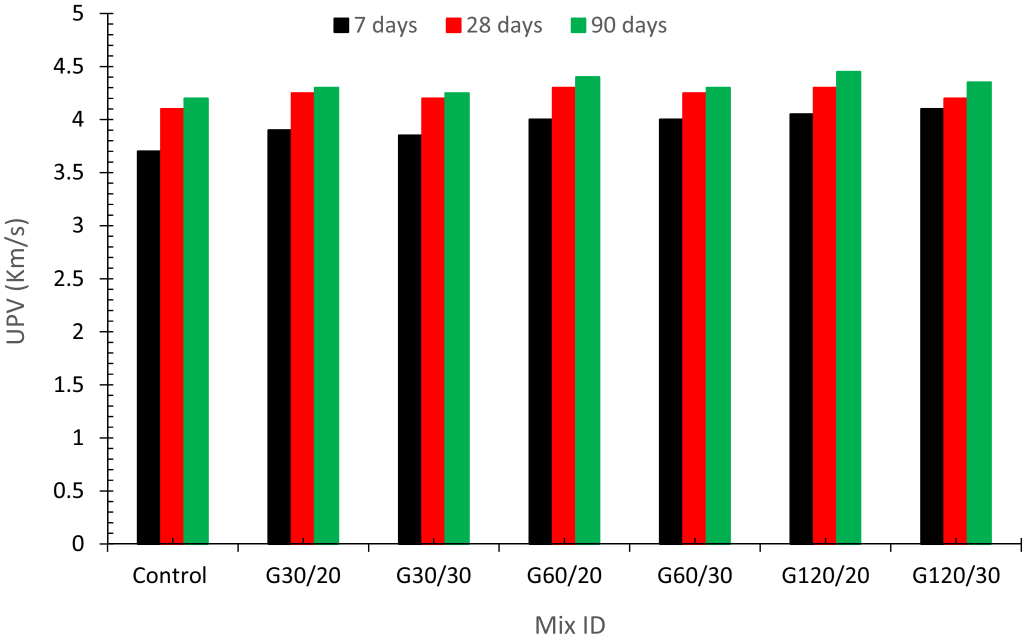

Fig. 17 Ultrasonic pulse velocity (Qudoos et al., 2018)

pronounced when finer ash particle inclusion was used. The G30/20 samples showed an increase above the reference samples of 4.6%, 2.5%, and 1% at 7 days, 28 days, and 90 days, respectively. In comparison to mortar samples containing 0% WTSA particles, the UPV for the mortar samples containing 20% G60-type ashes was 6.7%, 3.7%, and 2.4% larger at 7, 28, and 90 days of curing, respectively. Additionally, the UPV values for the G120/20 samples were 6.9 percent higher in comparison to the reference samples. By substituting a 20 percent finer WTSA for cement, the data shown above clearly demonstrate that it is possible to produce a blended cement of greater quality.

5.4 Alkali-Silica Reaction

Fig. 18 depicts the results of the ASR expansion. Based on Fig. 18, it can be shown that the ASR expansion of mortar containing 7 percent and 14 percent WTSA was less than that of the control mortar. When compared to a control mortar, WTSA mortar bars with 7 percent and 14 percent WTSA reduce ASR growth by 14 percent and 34 percent respectively. As a result, the inclusion of WTSA had a beneficial impact when utilized as a substitute for cement. The ASR expansion of cement and concrete is controlled by extra cementitious materials, according to a study (Thomas, 2011). This is accomplished by lowering the amount of alkalis that are accessible to react with the aggregate (Thomas, 2011).

Additionally, the CaO/SiO$_2$ ratio of the supplemental cementitious material has a strong correlation with its ability to adhere to other materials. Utilizing more cementitious materials with higher levels of silica and lower levels of silica in cementitious materials is the most effective technique to reduce the alkalinity of the pore solution. On the other hand, the values of ASR expansion exceeded 0.2 percent, which is the maximum allowed level of ASR growth. According to ASTM C 1260, there is a chance that aggregates may contain potentially dangerous compounds if the alkali silica expansion is more than 0.2 percent. A detailed analysis of the ASR test utilizing a variety of aggregates and testing conditions revealed that ASTM C 1260 often yields inaccurate results and suggested appropriate modifications (Golmakani, 2013).

5.5 Chloride Attacks

Fig. 19 shows the compressive strength of concrete samples that had been exposed to chlorine attack tests after 28 days of curing with and without the addition of WTSA. After the chloride attack, Sample 10 percent WTSA's compressive strength was 28.1 MPa, whereas Sample 40 percent WTSA's compressive strength was 30.75 MPa, which is higher than that of the control concrete sample. This shows that when WTSA concentration increased, the impact of chloride was reduced. This is because WTSA contains finer particles, which may better fill the concrete cavity and enhance the concrete's interfacial transition zone. Additionally, secondary cementitious materials produced by the pozzolanic reaction of WTSA aid in improving the interfacial transition zone of concrete. With the use of WTSA, less information is accessible on concrete chloride attacks and the review suggests details studies in this area.

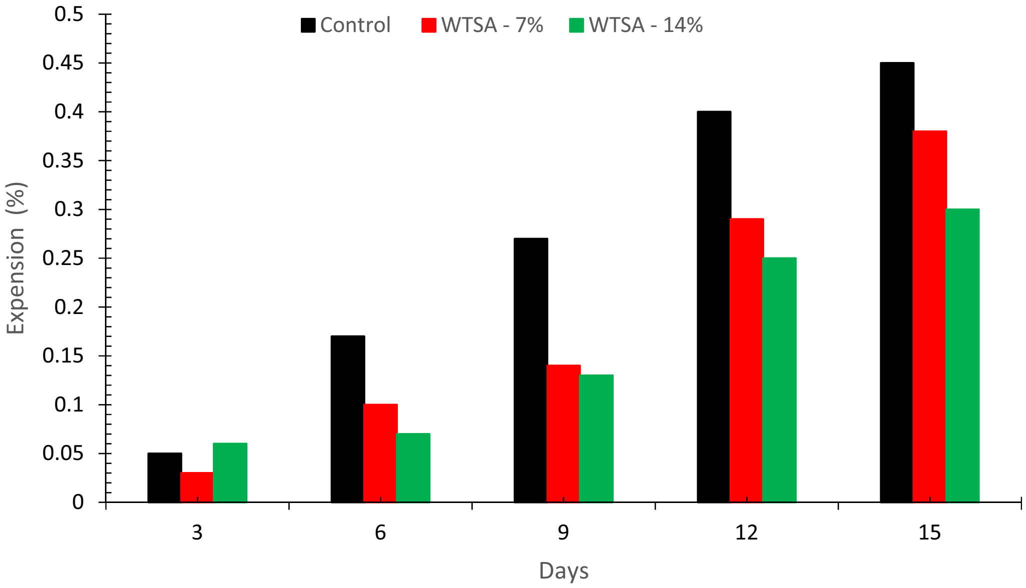

Fig. 18 ASR expansion (Ahmad et al., 2019)

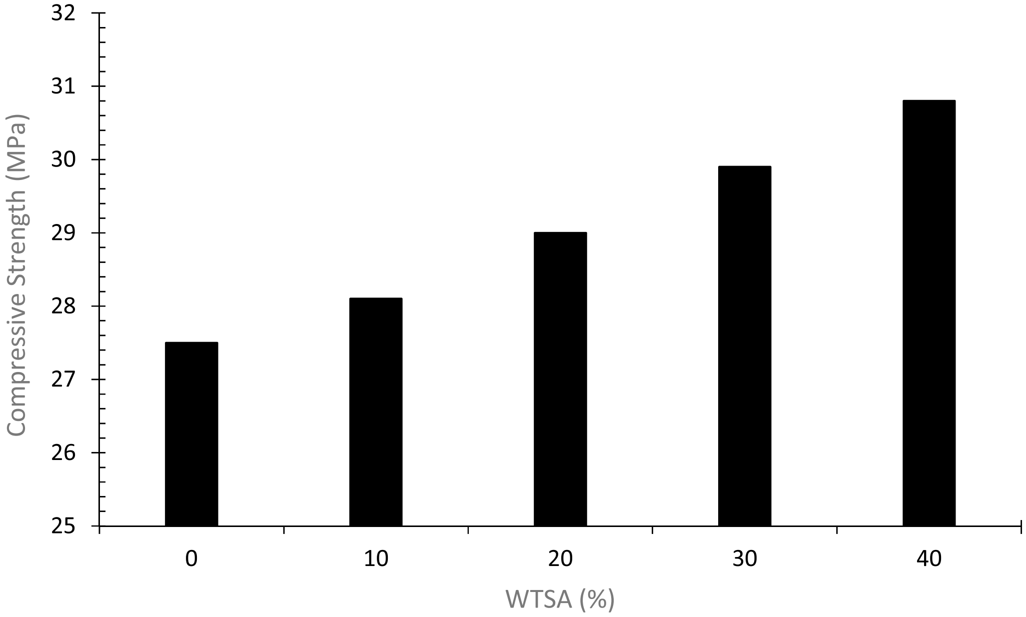

Fig. 19 Chloride attacks (Ahmad et al., 2019)

It can be concluded that the WTSA substitution improved the microstructure due to pozzolanic and filling voids of WTSA particles which decrease permeability, reduce the risk of alkali-silica reaction, and improved the resistance to acid attacks. These factors contribute to the increased service life of concrete structures.

6 Scanning Electron Microscopy (SEM)

The flow qualities of the concrete have a significant impact on the service life and durability of concrete buildings. The pore structure of the hydrated cement paste in particular is closely connected to these concrete flow capabilities. The impact of the addition of additives (WTSA) on the microstructure of concrete mortars was usually examined using a scanning electron microscope. Fig. 20 displays the SEM of the reference sample and the mortar samples contaning 20% replacement level of WTSA after 28 days of hydration.

The ashes were then ground for 30 (G30), 60 (G60), and 120 (G120) minutes in a laboratory ball mill. Instead of cement, a combination of 20% of each kind of WTSA was used. The mortar sample with 0% WTSA addition exhibits a porous microstructure and increased CH content, as seen by the SEM picture (Fig. 20a). The large, plate-like crystals that indicate the presence of gaps are contrasted with the dark patches that indicate the presence of CH crystals. On the other hand, the addition of WTSA led to the microstructure being denser as a consequence of both the filler and pozzolanic effects. The microstructure of the resultant ash was greatly improved when smaller WTSA particles (G60- and G120-type ashes) were introduced as compared to coarser WTSA particles (G30-type ash).

For instance, the micrographs (Fig. 20c, d) show that the bulk of the C–S–H gel has a compact structure and substantially less porosity. Due to the filler and pozzolanic action of the smaller WTSA particles, this results in a dense microstructure. A study also noted pozzolanic action produced greater CSH, less microcracks, and pores are produced, improving structural performance (AL-Kharabsheh et al., 2022). However, compared to mortar samples containing G60 and G120 ash particles, the microstructure of the mortar samples containing G30-type ash (Fig. 20b) showed a somewhat larger porosity and a smaller concentration of thick C–S–H gel. These results imply that the microstructure of the final products was enhanced by the addition of finer WTSA particles to the cement mortars. The pore structure improved and enhanced the mortar's strength.

7 Conclusions

Wheat is an agricultural crop that grows in subtropical climates. Straw is essentially a by-product and waste product of the wheat harvesting process. Straw is attracting the attention of a growing number of researchers and its usage as a cementitious ingredient in concrete is becoming more common. However, there is a need to investigate the use of straw in civil engineering applications in more detail. Therefore, the purpose of this study was to present the current research progress on WTSA

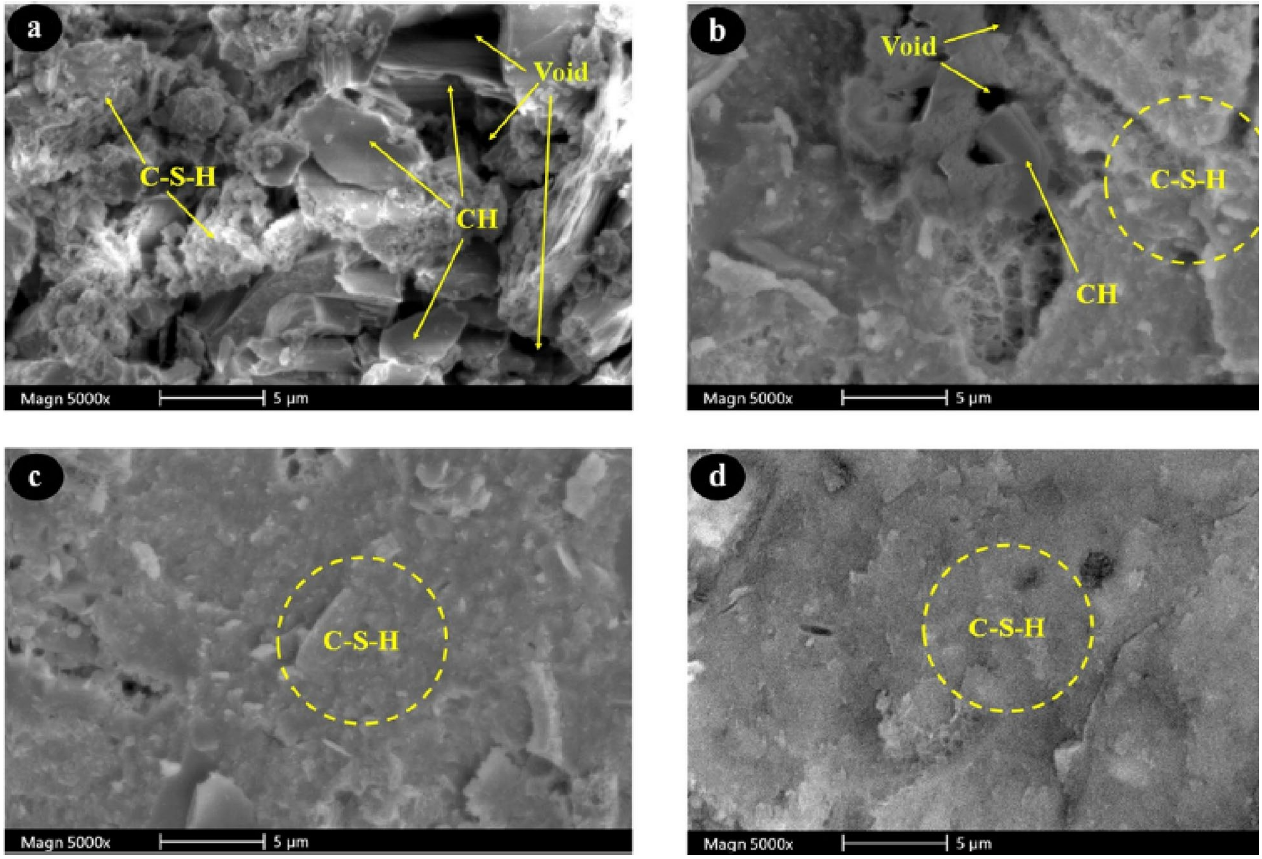

Fig. 20 SEM results, **a** reference, **b** G30, **c** G60, and **d** G120 (Qudoos et al., 2018)

and to suggest potential research aspects for the next generation. Based on the review, the following conclusion has been made.

- The chemical composition of WTSA demonstrates that it is suitable for usage as a cementitious material.
- The replacement of WTSA reduced the flowability of concrete. It is because WTSA particles are elongated, porous, and rough-textured.
- WTSA replacement lengthened initial and final setting times as the pozzolanic reaction progresses slowly as compared to the hydration of cement.
- With the replacement of WTSA, mechanical parameters including compressive strength, flexure strength, elastic modulus, and tensile strength enhanced. In comparison to reference concrete, the compressive strength of mixes including WTSA as a 5 and 10 percent substitute for cement is 8 and 12 percent greater, respectively. Higher dosages, however, result in a reduction in the mechanical performance of concrete because they are less flowable. Consequently, it is advised to utilize the recommended dosage. Depending on the source, aggregate, water-to-binder ratio, and mix design of the concrete, the usual optimal dosage of WTSA ranges from 10 to 20%.
- With the addition of WTSA, concrete's durability performance improved due to filling voids as well as pozzolanic reaction. However, there is less data available in this area.
- The addition of WTSA significantly reduced the expansion caused by the alkali-silica reaction.
- According to SEM findings, WTSA enhanced the concrete's interfacial transition zone by micro-filling and pozzolanic reaction.

8 Recommendations for Future Research

- Detail investigation of durability performance particularly creep and dry shrinkage properties should be conducted.
- The heating effects of WTSA at different temperatures should be investigated.

- Detail study should be conducted on thermogravimetric analysis and Fourier transform infrared spectroscopy.
- To increase the tensile capacity of WTSA-based concrete, fibre should be added.

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Author contributions
JA = writes the original draft. MMA = data collection and software work, MA = methodology and funding. FA = conceptual and funding. AFD = supervision, reviewed, and edited. All authors read and approved the final manuscript.

Availability of data and materials
All the materials are available in the main text.

Declarations

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Not applicable.

Consent for publication
Not applicable.

Competing interests
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