Utilization of Straw Ash as a Partial Substitute for Ordinary Portland Cement in Concrete

Liang Wen,[a,b,]* Changhong Yan,[c] Yehui Shi,[d] Zhenxiang Wang,[d] Gang Liu,[d] and Wei Shi [d]

The disposal of agricultural waste ash is a great ecological challenge. This study analyzed the basic properties of corn straw ash and soybean straw ash, encompassing the identification of key oxides, the assessment of particle size distribution, and the performance of thermogravimetric analysis. This study also evaluated the potential of corn straw ash and soybean straw ash to replace cement in mortar and concrete through laboratory tests. The findings indicated that the strength activity index of corn straw ash was higher than soybean straw ash. Furthermore, when these ashes were used as cement replacements, the compressive strength of concrete decreased. Notably, concrete containing corn straw ash exhibited greater strength than concrete with the same substitution amount of soybean straw ash. Specifically, at a 5% substitution level, the compressive strengths of corn straw ash concrete and soybean straw ash concrete were 31.5 and 30.5 MPa, respectively. Additionally, soybean straw ash concrete demonstrated superior resistance to water penetration compared to corn straw ash concrete. Both corn straw ash and soybean straw ash exhibited the potential to enhance the early crack resistance of concrete.

DOI: 10.15376/biores.19.3.4250-4263

Keywords: Straw ash; Concrete; Unconfined compressive strength; Resistance of concrete water penetration; Cracking resistance

*Contact information: a: Tunnel and Underground Engineering Research Center of Jiangsu Province (TERC), Nanjing 210041, Jiangsu, China; b: School of Civil Engineering and Architecture, Anhui University Science and Technology, Huainan 232001, Anhui, China; c: School of Earth Sciences and Engineering, Nanjing University, Nanjing 210023, Jiangsu, China; d: The First Geological Brigade of Jiangsu Geology and Mineral Exploration Bureau, Nanjing 210041, Jiangsu, China; *Corresponding author: lwen@aust.edu.cn*

INTRODUCTION

China is a large agricultural country, annually generating vast quantities of straw. Straw serves as an abundant source of combustible materials for power generation. However, the disposal of industrial ash, particularly the biomass ash generated by biomass power plants, such as rice husk ash and corn cob ash, poses significant challenges (Athira and Bahurudeen 2022; Ruan *et al.* 2022; Santhosh *et al.* 2022). Rice husk ash, rich in amorphous silica, has been identified by numerous researchers as a viable cementitious material for use in engineering materials (Antiohos *et al.* 2014; Wei and Meyer 2016; Yan *et al.* 2022). The study of other biomass ashes and whether they can improve the mechanical properties of concrete is of great significance for the utilization of biomass ash resources.

With the development of industrial buildings, a large amount of concrete will be needed (Yurt and Bekar 2022). Cement is one of the most important materials of concrete. It has an important effect on strength and durability. The production process of cement is complex and requires many raw materials.

Many scholars aim to reduce the waste of natural resources in cement production by different methods (Teixeira *et al.* 2022). Global concrete production exceeds 10 billion tons per year, so cement consumption is also very large. The production of cement would produce large amounts of gaseous wastes, solid wastes, and wastewaters that will cause pollution to the environment. Environmental pollution can be decreased by reducing the consumption of cement (Wu *et al.* 2018; Tavares *et al.* 2022; Yan *et al.* 2022; Yurt and Bekar 2022).

Biomass ash has pozzolanic properties and can be effectively used as an auxiliary cementitious material in cement-based materials (Wang *et al.* 2008). Studies have found that many types of crop biomass ash have certain activities, such as sugarcane straw ash (Martirena *et al.* 2006), and wheat straw ash (Jankovsky *et al.* 2017; Supic *et al.* 2021). With the development of science and technology, the development of agricultural straw ash in construction is increasingly worthy of attention, and its application is beneficial to environmental protection (Rosales *et al.* 2016).

The chemical compositions of various biomass ashes are different (Adhikary *et al.* 2022). They have a strong relationship with temperature and collection methods (Fontes *et al.* 2019). The fineness of particles in the biomass ash will also affect its activity, and many biomass ash specimens need to be ground in preparation for experiments (Agarwal 2006; Antiohos *et al.* 2014). Thus, the kind of biomass ash and the methods used to obtain them can affect their properties.

There have been many studies dealing with the replacement of cement by ash in the preparation of concrete. Amin *et al.* (2021) reported that ash can lead to a decrease in slump flow, and replacing cement with nanocotton stalks and palm leaves ash can enhance the concrete strength. Tuan *et al.* (2011) found that the compressive strength of HPC was more favorable with 10% dosage of rice husk ash, and a larger ash particle size resulted in a smaller compressive strength. Ristić *et al.* (2021) reported that 10% dosage of biomass wood ash is conducive to increase concrete strength. Andrade Neto *et al.* (2021) reported that sugarcane bagasse ash has a high pozzolanic activity when calcined at 600 °C. The resulting material showed the ability to reduce the porosity and sorptivity of the concrete. It also was able to enhance the compressive strength and increase the concrete carbonization rate.

There are many types of straw ashes, and the application of straw ash to concrete can not only solve the environmental problems caused by straw ash, but it also can realize the resource utilization of straw ash, replacing the cement also can save the raw materials in concrete and reduce the production cost.

In this paper, the properties of corn straw ash (CSA) and soybean straw ash (SSA) were studied, and the effect of straw ash on the concrete using CSA and SSA to replace ordinary Portland cement in concrete was also studied, including the compressive strength, impermeability, crack resistance, and so on. The results in this paper have significance in the utilization of waste resources and will also provide sufficient scientific basis for the application in concrete.

EXPERIMENTAL

Materials

1) The naturally burned CSA and SSA were heated to 600 °C for 5 h, passed through a 200-mesh sieve, collected, and used as the test materials.

2) The ordinary Portland cement was P. O 42.5, the compressive strength of the specimen was 25.8 MPa at 3 days, and it was greater than 42.5 MPa at 28 days. The contents of MgO and SO_3 were 4.35% and 2.1%, the firing loss was 3.35%, the alkali content was less than 0.6%, and the specific surface area was 380 m^2/kg.

3) The coarse aggregate was continuous graded limestone gravel with a particle size of 5 mm to 15 mm, and the fine aggregate was river sand, which is a medium-sized sand, the packing density was 1380 kg/m^3, and the fineness modulus was 2.7.

4) Water reducing agent, polycarboxylate type, and laboratory tap water were added.

Methods

Strength activity index of straw ashes

The strength activity index of straw ashes was examined according to GB/T 1596 (2017). The strength activity index is defined as the ratio between the compressive strength of testing mortar and the reference mortar. The mass ratio of cement and standard sand was 1:3 for the reference mortar, and the testing mortar involved the replacement of 30% of the cement with either CSA or SSA. Both mortar samples were tested at 28 days. The strength activity index test mortar ratio is shown in Table 1.

Concrete strength test

The ordinary Portland cement, water, stone, and sand were evenly mixed, and then a water reducing agent was added. The mixing design for the concretes is shown in Table 2. Then, 100 mm × 100 mm × 100 mm concrete was prepared, left for 24 h, and then removed from the mold. It was then put into a standard thermostatic curing box with curing humidity $\geq$ 95% and curing temperature of 20 ± 2 °C (Yan *et al.* 2022). After 28 days of curing, the concrete sample was removed, and the surface water was wiped off for the compressive strength test. The test instruments are shown in Fig. 1(a).

Resistance of concrete water penetration test and early cracking of concrete test

Both tests were conducted according to GB/T 50082 (2009). The resistance of concrete water penetration test was measured by the gradual pressure loading method. The test instruments are shown in Fig. 1(b), and the substituted ordinary Portland content of CSA and SSA was 5% for the tests. During the test, the water pressure started from 0.1 MPa, and it increased 0.1 MPa every 8 h. The water seepage situation of the end face of the test specimen was observed. When the water seepage occurred on the surface of three specimens, the test was stopped, and the time was recorded. During the test, when water seeped from the perimeter of the specimen, it was re-sealed.

In the test for early cracking of concrete, the 800 mm × 600 mm × 100 mm flat sheet specimen was used. It was made of steel and the template can be disassembled. A steel crack inducer was installed inside the template and a polyethylene film was placed on the bottom plate. After the concrete was poured into the mold, the surface of the concrete is flattened and the surface should be slightly higher than the mold frame. The mould is shown in Fig. 1(c). It was used to vibrate the concrete manually. When the specimen was formed, after 30 min, the fan was used to blow the surface. The wind direction was parallel to the specimen surface and the crack inducer. The substituted level of ordinary Portland content by CSA and SSA was 5% for the tests to study the influence of CSA and SSA on the early cracking of concrete. The ambient temperature was 20 ± 2 ℃ and the humidity was approximately 60%. The cracks were observed with a magnifying glass with an accuracy of ≤ 0.01 mm.

Table 1. Strength Activity Index Test Mortar Ratio (g)

Samples	Cement	Water	Sand	CSA	SSA
Reference mortar	450	225	1350		
Testing mortar	315	225	1350	135	
	315	225	1350		135

Table 2. Mix Design of Concretes (kg/m^3)

Samples	Cement	Water	Stone	Sand	CSA	SSA	Water reducing agent
A	431	194	837	837			10.77
B	409.45	194	837	837	21.55		10.77
C	387.9	194	837	837	43.1		10.77
D	366.35	194	837	837	64.65		10.77
E	409.45	194	837	837		21.55	10.77
F	387.9	194	837	837		43.1	10.77
G	366.35	194	837	837		64.65	10.77


(a) (b) (c)

Fig. 1. Test equipment: (a) Compressive strength equipment, (b) Concrete impermeability equipment, and (c) Early cracking of concrete test mold

RESULTS AND DISCUSSION

Properties of CSA and SSA

The main oxides of straw ashes are shown in Table 3, as measured by X-ray fluorescence (XRF). The content of SiO_2 in CSA was 50.0%, and the content of SiO_2 in SSA was 25.2% which was one half of that in CSA. The contents of CaO and K_2O in CSA were 12.5% and 14.8%, which were one half of those in SSA, in which the contents of CaO and K_2O were 25.2% and 22.2%, respectively. The contents of Al_2O_3 and Fe_2O_3 were similar, whereas the content of MgO in the SSA was bigger than that of CSA, which was

7.9%. The total content of $SiO_2 + Al_2O_3 + Fe_2O_3$ in CSA and SSA was 56.8% and 33.0%. The content of active ingredients in CSA was higher than that in SSA.

Table 3. The Main Oxides of CSA and SSA (%)

Straw Ash Type	CaO	SiO_2	Al_2O_3	MgO	SO_3	Fe_2O_3	K_2O
CSA	12.5	50.0	4.6	5.8	1.1	2.2	14.8
SSA	25.2	25.2	5.1	7.9	3.6	2.7	22.2

As shown in Fig. 2, the maximum particle sizes of the CSA and SSA were greater than 75 μm, which was inconsistent with the test condition. This result can be explained by some unscreened particles of straw ashes that became mixed in the grading analysis test. The difference in the particle size between CSA and SSA was concentrated in the 10 to 40 μm range, and the authors found that for the CSA particle size, the percentage of passing in the 10 to 40 μm range was smaller than that of SSA. In Fig. 3, it can also be concluded that the main mineral compositions of the ashes were quartz, calcite, sylvite, and so on. Through XRD, the XRD intensity of quartz in CSA was greater than that of SSA, but for sylvite, it was the opposite. As shown in Fig. 4, there was a large difference in surface color between CSA and SSA, where CSA surface color was dark gray and SSA surface color was gray. The authors also found that slag formation occurred in the calcination process of CSA and SSA.

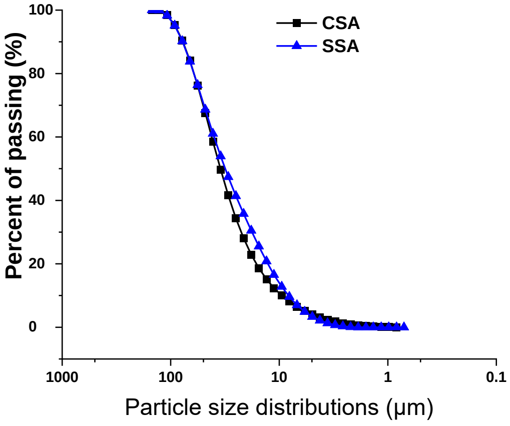

Fig. 2. The particle size distribution of straw ashes

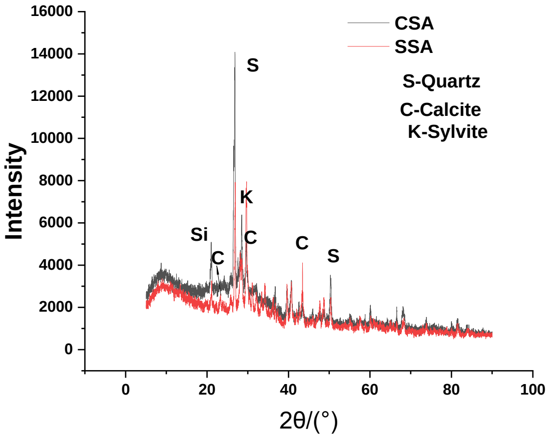

Fig. 3. The XRD of the straw ashes

Fig. 4. CSA and SSA samples

The mass of untreated CSA and SSA decreases with the increase of temperature. When the temperature reached 900 °C, the mass fraction of CSA decreased to 82.9%, while the mass fraction of SSA decreased to 75.6%. This means that the CSA and SSA quality decreased 17.1% and 24.4%, respectively, which can be seen from Fig. 5. The weight loss rate of CSA and SSA is faster at 100 °C. This was due to the fact that water in the straw ash was lost due to the heat. The CSA and SSA used in the concrete test are calcinated at 600 °C, the properties of CSA and SSA before this temperature have little effect on the study. There is also a large peak weight loss rate between 600 and 800 °C. This was because some substances volatilize at high temperatures, such as sylvite. The weight loss value of SSA was greater than that of CSA. This may be related to the higher sylvite content in SSA. In concrete, the best calcination temperature of different biomass ash is not the same. Perhaps the calcination temperature of biomass should be controlled between 600 and 800 °C. In this paper, the performances of CSA and SSA in concrete were studied only at the calcination temperature of 600 °C.

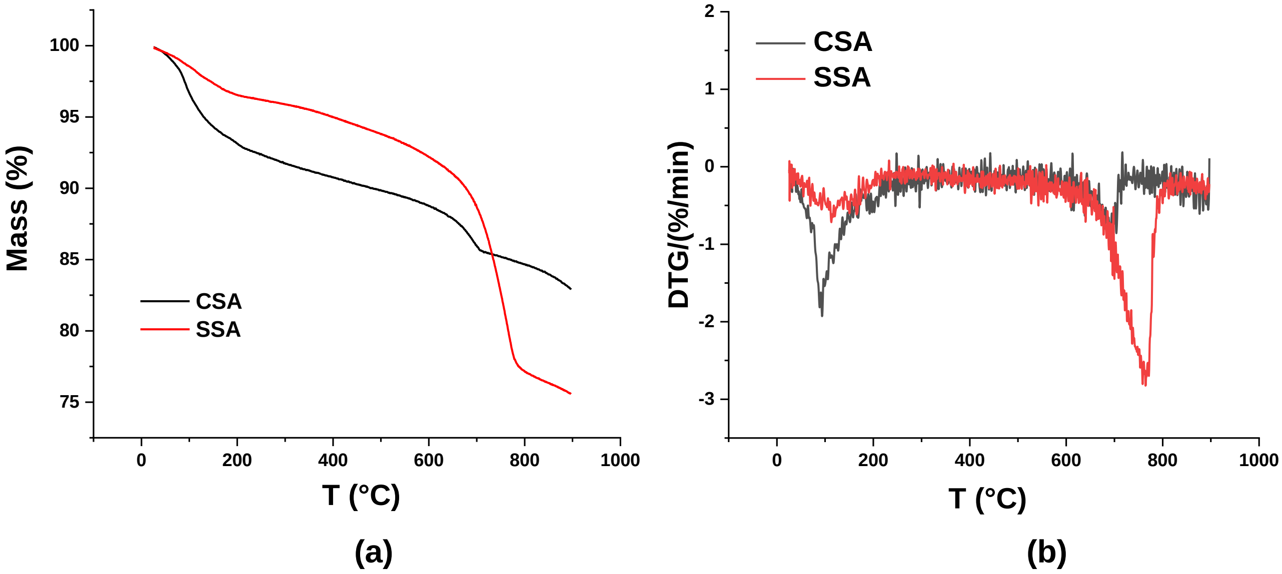

Fig. 5. TG-DTG of CSA and SSA (a): TG curves, (b) DTG curves

Properties of Straw Ash Concrete

Strength activity Index

The strength activity index results of both tests are presented in Fig. 6. According to the criteria given in standard GB/T 1596 (2017), the activity index at 28 days shall not be less than 70%. The CSA concrete was able to meet these requirements, while SSA concrete samples did not meet the standard at the age of 28 days. This may be because the amount of reactive silica was higher than that for the SSA. This means that, based on the present results, CSA can be used in cement to a certain extent as an active mixture of cement, whereas SSA as an active mixture of cement has low activity and worse performance than CSA in the cement mortar.

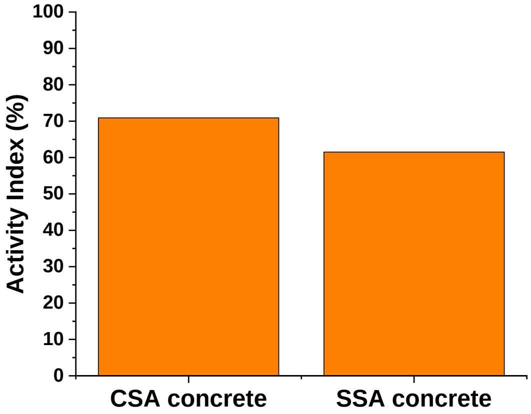

Fig. 6. Strength activity index of straw ashes

Compressive strength

As shown in Fig. 7, the compressive strength of concrete was 31.5 MPa, which was decreased 7.9% with 5% CSA addition, and the compressive strength of concrete was 30.5 MPa, which was decreased 10.8% with 5% SSA addition. It was found that added straw ash was not able to improve the compressive strength of concrete, but when the dosage of straw ash added was small, the strength decreased little compared with the original concrete. This indicates that straw ash can be feasibly to be applied to concrete when the concrete is not very strict in strength (Zhang *et al.* 2017). The compressive strength of CSA concrete was stronger than that of SSA concrete with the same dosage addition. This was because the contents of SiO_2 and $SiO_2 + Al_2O_3 + Fe_2O_3$ were more than that of SSA, as shown in Table 3. A better activity of straw ash results in the more beneficial to improve the strength of concrete. The compressive strength of straw ash concrete is related to not only the type of straw ash but also the dosage of the straw ashes. When the dosage of straw ash increased, the compressive strength decreased. This also indicated that the straw ash cannot compensate for the influence of cement on the strength of concrete with the same amount. But in research on the application of straw ash in concrete, straw ash replacing fine aggregates also can effectively improve the strength, which has been shown by the tests (Binici *et al.* 2008; Rahimi *et al.* 2015; Supic *et al.* 2021).

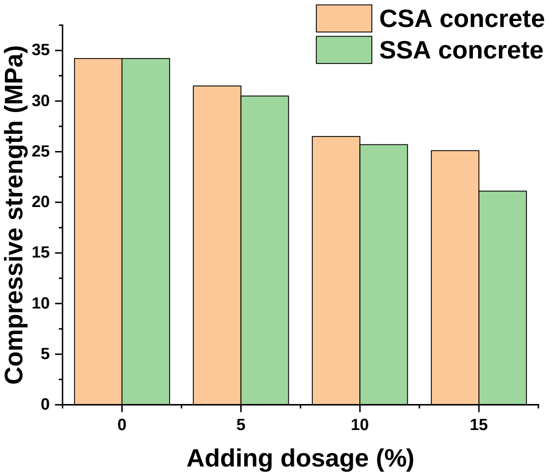

Fig. 7. Concrete strength changes with different straw ash dosages

Resistance of concrete water penetration

As shown in Fig. 8, the resistance of concrete to water penetration decreased noticeably with the addition of CSA, and as for the SSA, the impermeability of SSA concrete was similar to that of original concrete. However, compared the SSA concrete with the original concrete, water seepage in the third concrete specimen began to occur when the water pressure was 1.0 MPa, which lasted for 1 h, and the water pressure was 1.0 MPa, which was lasted for 6 h for the original concrete. The resistance of concrete to water penetration of SSA concrete still decreased compared with the original concrete. From Fig. 7, it is apparent that the replacement of an equal dosage of the Portland cement by CSA can reduce the compressive strength and the resistance of concrete water penetration. The compressive strength of CSA concrete was greater than that of SSA concrete, but the resistance of concrete to water penetration was weaker than that of SSA concrete. This indicates that the activity of CSA was greater than that of SSA when replacing an equal dosage of Portland cement. Being a porous structure, concrete must have seepage channels inside, and these can have a great impact on the resistance of concrete water penetration. Cutting off seepage channels and reducing the number of water-conducting pores formed in the hardening process of concrete is an effective way to improve the permeability resistance of concrete (Chen *et al.* 2005; Zhang *et al.* 2015). Straw ashes have pozzolanic activity and particle filling properties, pozzolanic activity plays a major role in the strength, while the particle filling properties mainly affect the pore structure of concrete, and the concrete impermeability is mainly related to the pore structure. When the straw ash is added to concrete, the particle filling effect of CSA is weaker than that of SSA, and then the impermeability of concrete will decrease, the particle filling effect of SSA on concrete is stronger than that of CSA. Figure 9 shows the concrete seepage pattern after the concrete impermeability test, which can reflect the water seeping through internal channels in the concrete under the pressure.

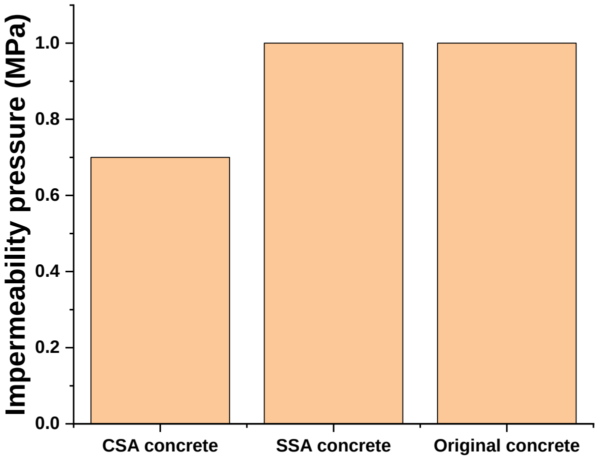

Fig. 8. The concrete impermeability

Fig. 9. Impermeability test diagram

Early cracking resistance of concrete

As shown in Fig. 10, the total cracking area and the number of cracks per unit area of the ordinary concrete were larger than that of CSA and SSA. The concrete cracking diagram is shown in Fig. 11. The total cracking area of original concrete was the largest, followed by CSA concrete, and the total cracking area of SSA concrete was the smallest.

The number of cracks per unit area was the largest for original concrete, followed by CSA concrete, and the last was SSA concrete. The average cracking area was the largest for SSA concrete, followed by CSA concrete, and finally original concrete. When the internal tensile stress of concrete is greater than the tensile strength of concrete, the concrete will have an early cracking phenomenon, and the water-cement ratio, cementing materials, and curing conditions all have important effects on the early cracking of concrete (Ba and Su 2006). It may have a strong relationship with the release of hydration heat in the hydration hardening process of gelled materials and the adsorption of water of the concrete. After replacing cement with straw ash, the compressive strength of concrete partially decreases, the hydration heat in the cement reaction process is also reduced due to the reduction in cement content, which promotes the reduction of cracks in concrete.

The cracking of concrete can affect the concrete structure to a certain extent, and then it can affect the strength of concrete in terms of water permeability. Due to the particularity of concrete materials, the cracking phenomenon of concrete cannot be eliminated, but some measures can be taken to reduce the concrete cracks. Such measures have great significance for the application of concrete in civil engineering.

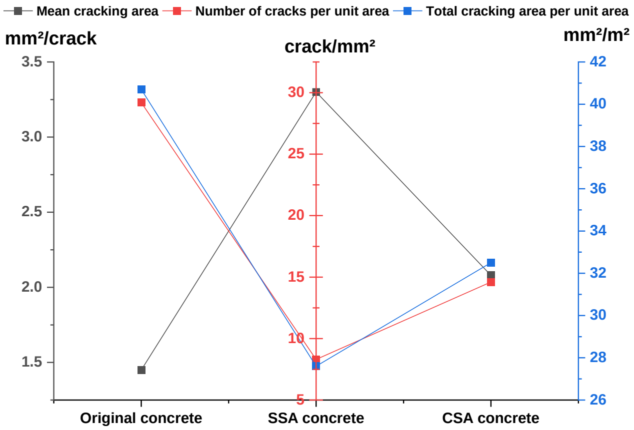

Fig. 10. Early crack resistance of concrete

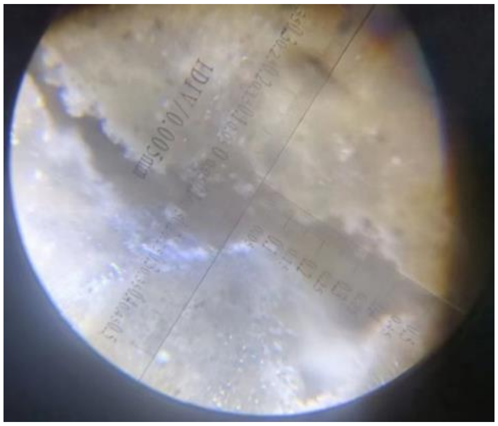

Fig. 11. Concrete cracking diagram

Concrete density

As can be seen in Fig. 12, the density of concrete showed a declining trend with increasing dosage of the CSA or SSA. With an equal dosage, the density of CSA concrete was larger than that of SSA concrete, and the difference between the CSA concrete and SSA concrete densities gradually increased with increasing dosage. The density of CSA concrete was 1.4% higher than that of SSA concrete and 8.8% lower than that of original concrete with 15% straw ash dosage. The concrete density decreased 0.4% to 8.8% when CSA was added in the 5% to 15% range, whereas it was 1.3% to 10.0% for the SSA. This may be because the activity of straw ash was not as high as cement, and the amount of gel produced in the reaction process was less than that of cement, thus reducing the density. The increase in the dosage of straw ash will reduce the amount of cement, so that the quality will also decline and the density will become smaller.

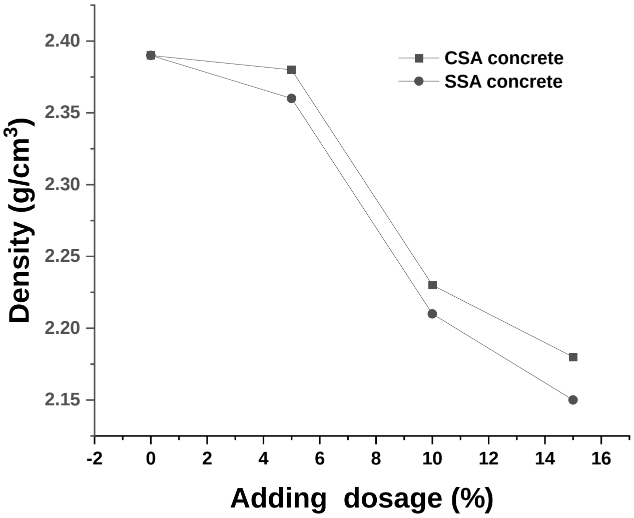

Fig. 12. Density of straw ash concrete

DISCUSSION

In practical applications, the resistance of concrete water penetration is affected by the environmental conditions and service life period, and it is one of the durability indexes of concrete. The poor resistance of concrete to water penetration has a serious impact on the quality and safety of the structure. The resistance of concrete to water penetration is related to multiple factors, including the water-cement ratio, porosity, pore size, and the interface contact between the aggregate and matrix (Li *et al.* 2004; Chen *et al.* 2005). These factors affect the permeability of concrete by affecting the internal pores of the concrete, the concrete pores can be divided into: macropore, capillary pores, transition pores, and gel pores, and the pore size affecting the permeability of concrete is generally greater than 100 nm (Li *et al.* 2004; Chen *et al.* 2005). The resistance of concrete to water penetration is related not only to the size and number of pores, but also to the connectivity of the pores. The connectivity of the internal pores of concrete can provide an effective water seepage channel, and the size of the pores becomes a necessary condition for water seepage in the connected pores. To improve the impermeability of concrete, it is concluded from the aspect of pores: (1) reducing the number of effective pores generated inside the concrete; (2) filling the existing effective pores, reduce the size of effective pores, and form invalid pores; (3) blocking through the pores and cut off of seepage channels.

Straw ash has pozzolanic activity and particle filling properties that are similar to fly ash (Wei *et al.* 2021; Xiao and Yue 2023). The active SiO_2 and Al_2O_3 in straw ash react chemically with $Ca(OH)_2$. From the above tests, the authors learned that CSA and SSA could not improve the unconfined compressive strength of concrete at 28 days by replacing the same dosage of cement in concrete. When CSA and SSA replace Portland cement, the compressive strength follows the order of ordinary concrete > CSA concrete > SSA concrete. The resistance of the concrete to water penetration follows the order of original concrete > SSA concrete > CSA concrete. The performance of CSA concrete and SSA concrete was not as good as that of original concrete. The heat of hydration causes shrinkage and cracks in the process of Portland cement hydration and hardening, which will affect the unconfined compressive strength and the resistance of concrete water penetration (Li *et al.* 2022). The original concrete was still in good condition. Replacing Portland cement with straw ash can reduce the hydration heat in the hydration hardening process of cement. Meanwhile, the filling property of straw ash can also fill the effective seepage pores in concrete and reduce the seepage channels. The decreases in compressive strength and the resistance of straw ash concrete water penetration were mainly caused by the decrease of cement content. The variations in the strength of CSA concrete and SSA concrete are caused by the different pozzolanic activities, and their different impermeabilities are mainly caused by the different particle filling effects. Figure 2 shows the distribution of straw ash particles in concrete. Some of those participate in the hydration hardening of cement, and some fill the internal pores of concrete. The chemical reaction is conducive to improving the strength of straw ash concrete, and the filling is conducive to improving the anti-seepage performance of straw ash concrete, or both at the same time.

The test results showed that the particle size and chemical composition of straw ash had a great impact on the performance of concrete. Calcination and grinding methods can also increase the pozzolanic activity of the ash that are often used for concrete (Thomas *et al.* 2021). However, the properties of different biomass ashes differ greatly. They have different effects on the performance of concrete after replacing Portland cement. When the cement was replaced by CSA and SSA, the strength of concrete decreased slightly. Therefore, to be safe, they cannot replace Portland cement in large quantities.

CONCLUSIONS

1. The content of SiO_2 in CSA was 50.5%, which was higher than that in SSA. The contents of CaO and K_2O were lower than those in SSA. The CSA particle size that passed in the 10 μm to 40 μm range was smaller than that of SSA, when the temperature reached 900 °C, the mass fraction of the untreated CSA decreased to 82.9%, while the mass fraction of the untreated SSA decreased to 75.6%.
2. The strength activity index of CSA was higher than SSA, and the strength of CSA concrete was greater than that of SSA with the same dosage. The compressive strength of concrete was decreased by replacing an equal amount of Portland cement with straw ash. The permeability resistance of SSA concrete was stronger than that of CSA concrete, and the cracking resistance of straw ash concrete was improved.
3. Straw ash reduced the density of concrete. The concrete density was reduced by 0.4% to 8.8% when CSA was added at the 5% to 15% levels. For the SSA, the concrete was reduced 1.3% to 10.0%.
4. Both CSA and SSA should not be added to concrete in excess. The recommended dosage of addition is 5%. This dosage of CSA and SSA in concrete can make strength and impermeability meet the engineering requirements. It also can improve the early cracking resistance, and it can also save costs in concrete. CSA is the preferred choice compared to SSA.

ACKNOWLEDGMENTS

The authors are grateful for the support of the Opening Project of Tunnel and Underground Engineering Research Center of Jiangsu Province (TERC), Grant No. 2021-SDJJ-08.

REFERENCES CITED

Adhikary, S. K., Ashish, D. K., and Rudzionis, Z. (2022). "A review on sustainable use of agricultural straw and husk biomass ashes: Transitioning towards low carbon economy," *Science of The Total Environment* 838(Part 3), article ID 156407. DOI: 10.1016/j.scitotenv.2022.156407

Agarwal, S. K. (2006). "Pozzolanic activity of various siliceous materials," *Cement and Concrete Research* 36(9), 1735-1739. DOI: 10.1016/j.cemconres.2004.06.025

Amin, M., Zeyad, A. M., Tayeh, B. A., and Saad Agwa, I. (2021). "Effects of nano cotton stalk and palm leaf ashes on ultrahigh-performance concrete properties incorporating recycled concrete aggregates," *Construction and Building Materials* 302, article ID 124196. DOI: 10.1016/j.conbuildmat.2021.124196

Andrade Neto, J. d. S., de França, M. J. S., Amorim Júnior, N. S. d., and Ribeiro, D. V. (2021). "Effects of adding sugarcane bagasse ash on the properties and durability of concrete," *Construction and Building Materials* 266, article ID 120959. DOI: 10.1016/j.conbuildmat.2020.120959

Antiohos, S. K., Papadakis, V. G., and Tsimas, S. (2014). "Rice husk ash (RHA) effectiveness in cement and concrete as a function of reactive silica and fineness," *Cement and Concrete Research* 61-62, 20-27. DOI: 10.1016/j.cemconres.2014.04.001

Athira, G., and Bahurudeen, A. (2022). "Rheological properties of cement paste blended with sugarcane bagasse ash and rice straw ash," *Construction and Building Materials* 332, article ID 127377. DOI: 10.1016/j.conbuildmat.2022.127377

Ba, H., and Su, A. (2006). "Study on early-age cracking of high strengh concrete under circumferentially restrained condition," *Journal of Southeast University (Natural Science Edition)* 36(S(II)), 116-121.

Binici, H., Yucegok, F., Aksogan, O., and Kaplan, H. (2008). "Effect of corncob, wheat straw, and plane leaf ashes as mineral admixtures on concrete durability," *Journal of Materials in Civil Engineering* 20(7), 478-483. DOI: 10.1061/(ASCE)0899-1561(2008)20:7(478)

Chen, L., Wang, Y., Yin, X., and Zhang, D. (2005). "Effect of aperture size on impermeability of concrete," *Journal of the Chinese Ceramic Society* 33(4), 500-505. DOI: 10.14062/j.issn.0454-5648.2005.04.017

Fontes, C. M. A., Silva, R. B., and Lima, P. R. L. (2019). "Characterization and effect of using bottom and fly ashes from co-combustion of cocoa waste as mineral addition in concrete," *Waste and Biomass Valorization* 10(1), 223-233. DOI: 10.1007/s12649-017-0031-x

GB/T 1596 (2005). "Fly ash used for cement and concrete," Standardization Administration of China, Beijing, China.

GB/T 50082 (2009). "Standard for test methods of long-term perforance and durability of ordinary concrete," Ministry of Housing and Urban-Rural Development of the People's Republic of China, Beijing, China.

Jankovsky, O., Pavlíková, M., Sedmidubský, D., Bouša, D., Lojka, M., Pokorný, J., Záleská, M., and Pavlík, Z. (2017). "Study on pozzolana activity of wheat straw ash as potential admixture for blended cements," *Ceramics - Silikaty* 61(4), 327-339. DOI: 10.13168/cs.2017.0032

Li, H., Chen, M., Yang, Y., and He, Z. (2022). "Analysis of micro-strain characteristics of low-heat mass concrete," *Science Technology and Engineering* 22(22), 9746-9752.

Li, S., Zhao, T., and Wu, K. (2004). "Relationship between permeability and microstructure of concrete," *China Concrete and Cement Products* (02), 6-8. DOI: 10.19761/j.1000-4637.02.002

Martirena, F., Middendorf, B., Day, R. L., Gehrke, M., Roque, P., Martínez, L., and Betancourt, S. (2006). "Rudimentary, low tech incinerators as a means to produce reactive pozzolan out of sugar cane straw," *Cement and Concrete Research* 36(6), 1056-1061. DOI: 10.1016/j.cemconres.2006.03.016

Rahimi, A., Dogmechi, S. F., and Daemi, M. R. (2015). "Utilization of wheat stalk ash in concrete (an experimental study)," in: *The Annual International Civil, Architecture and Urbanism Conference (ICAUC2015)*, Kharazmi Higher Institute of Science and Technology, Shiraz, Iran.

Ristić, N., Grdić, Z., Topličić-ćurčić, G., Grdić, D., and DodevskI, V. (2021). "Properties of self-compacting concrete produced with biomass wood ash," *Tehnicki Vjesnik [Technical Gazette]* 28(2), 495-502. DOI: 10.17559/tv-20200214103332

Rosales, J., Beltrán, M. G., Cabrera, M., Velasco, A., and Agrela, F. (2016). "Feasible use of biomass bottom ash as addition in the manufacture of lightweight recycled concrete," *Waste and Biomass Valorization* 7(4), 953-963. DOI: 10.1007/s12649-016-9522-4

Ruan, S., Su, L., Ou, H., Lin, W., Jiang, S., and Sun, F. (2022). "Study on heat and mass transfer performance during heating, pressurization and expansion stage in explosion puffing at low temperature and high-pressure," *Energies* 15, article ID 7896. DOI: 10.3390/en15217896

Santhosh, K. G., Subhani, S. M., and Bahurudeen, A. (2022). "Recycling of palm oil fuel ash and rice husk ash in the cleaner production of concrete," *Journal of Cleaner Production* 354, article ID 131736. DOI: 10.1016/j.jclepro.2022.131736

Supic, S., Malesev, M., Radonjanin, V., Bulatovic, V., and Milovic, T. (2021). "Reactivity and pozzolanic properties of biomass ashes generated by wheat and soybean straw combustion," *Materials (Basel)* 14(4), article 1004. DOI: 10.3390/ma14041004

Tavares, J. C., Lucena, L. F. L., Henriques, G. F., Ferreira, R. L. S., and dos Anjos, M. A. S. (2022). "Use of banana leaf ash as partial replacement of Portland cement in eco-friendly concretes," *Construction and Building Materials* 346, article ID 128467. DOI: 10.1016/j.conbuildmat.2022.128467

Teixeira, E. R., Camões, A., and Branco, F. G. (2022). "Synergetic effect of biomass fly ash on improvement of high-volume coal fly ash concrete properties," *Construction and Building Materials* 314, article ID 125680. DOI: 10.1016/j.conbuildmat.2021.125680

Thomas, B. S., Yang, J., Mo, K. H., Abdalla, J. A., Hawileh, R. A., and Ariyachandra, E. (2021). "Biomass ashes from agricultural wastes as supplementary cementitious materials or aggregate replacement in cement/geopolymer concrete: A comprehensive review," *Journal of Building Engineering* 40, article ID 102332. DOI 10.1016/j.jobe.2021.102332

Van Tuan, N., Ye, G., van Breugel, K., Fraaij, A. L. A., and Bui, D. D. (2011). "The study of using rice husk ash to produce ultra high performance concrete," *Construction and Building Materials* 25(4), 2030-2035. DOI: 10.1016/j.conbuildmat.2010.11.046

Wang, S., Miller, A., Llamazos, E., Fonseca, F., and Baxter, L. (2008). "Biomass fly ash in concrete: Mixture proportioning and mechanical properties," *Fuel* 87(3), 365-371. DOI: 10.1016/j.fuel.2007.05.026

Wei, J., Li, S., Zhong, F., and Yi, C. (2021). "Multi-factor computation model of compressive strength of biomass-based concrete," *Concrete* (09), 63-68+72. DOI: 10.3969/j.issn.1002-3550.2021.09.012

Wei, J., and Meyer, C. (2016). "Utilization of rice husk ash in green natural fiber-reinforced cement composites: Mitigating degradation of sisal fiber," *Cement and Concrete Research* 81, 94-111. DOI: 10.1016/j.cemconres.2015.12.001

Wu, F., Liu, C., Zhang, L., Lu, Y., and Ma, Y. (2018). "Comparative study of carbonized peach shell and carbonized apricot shell to improve the performance of lightweight concrete," *Construction and Building Materials* 188, 758-771. DOI: 10.1016/j.conbuildmat.2018.08.094

Xiao, L., and Yue, X. (2023). "Effect of synergistic effect of rice husk ash composite mineral admixture and fiber on mechanical properties and impermeability of subway concrete," *Applied Chemical Industry* 52(01), 102-105+111. DOI: 10.16581/j.cnki.issn1671-3206.2023.01.002

Yan, K., Lan, H., Li, Q., Ge, D., and Li, Y. (2022). "Optimum utilization of recycled aggregate and rice husk ash stabilized base material," *Construction and Building Materials* 348, article ID 128627. DOI: 10.1016/j.conbuildmat.2022.128627

Yurt, Ü., and Bekar, F. (2022). "Comparative study of hazelnut-shell biomass ash and metakaolin to improve the performance of alkali-activated concrete: A sustainable greener alternative," *Construction and Building Materials* 320, article ID 126230. DOI: 10.1016/j.conbuildmat.2021.126230

Zhang, Q., Li, Y., Liu, B., and Xu, Z. (2017). "Mechanical properties and strength prediction of straw ash concrete," *Transactions of the Chinese Society of Agricultural Engineering* 33(2), 259-265. DOI: 10.11975/j.issn.1002-6819.2017.02.036

Zhang, T., Wang, Z., Zhu, H., Zheng, G., and He, X. (2015). "Permeability of yellow river superfine sand plastic concrete," *Journal of Sichuan University (Engineering Science Edition)* 47(04), 69-75. DOI: 10.15961/j. jsuese.2015.04.010

Article submitted: March 11, 2024; Peer review completed: April 6, 2024; Revised version received: April 13, 2024; Accepted: April 18, 2024; Published: May 9, 2024.
DOI: 10.15376/biores.19.3.4250-4263