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Evaluation of strength and electrical resistivity in cement mortars incorporating different biomass ashes

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Abstract
The high carbon emissions of cement production necessitate mitigation strategies. One approach is partial cement replacement, for which biomass ash, a waste of biomass combustion for energy production, could be a viable candidate. This study investigates the effects of hazelnut shell ash and sugar beet pulp ash as partial cement replacements. Biomass ash properties and effects on setting time, strength, ultrasonic pulse velocity (UPV), and electrical resistivity were evaluated. Electrical resistivity was measured by two methods, including a newly introduced DC-based technique utilizing an insulation resistance tester. While hazelnut shell ash accelerated final setting by 73 min, sugar beet pulp ash delayed final setting by 186 min at the same 15% replacement rate. Both ashes reduced compressive and flexural strength, with the degree of reduction increasing with replacement rate; this effect was more pronounced for hazelnut shell ash. At a 5% replacement, hazelnut shell ash reduced compressive strength by 17.2 MPa at 28 days and 22.8 MPa at 90 days, while sugar beet pulp ash caused a smaller decrease of 4.7 MPa and 9.5 MPa, respectively. These results suggest that sugar beet pulp ash has a greater potential for performance improvement after mechanical activation application. Hazelnut shell ash improved electrical resistivity by 7% to 10% at a 5% replacement for both measurement methods, respectively. The DC-based method showed a strong correlation with the conventional Wenner test, with a Spearman's correlation coefficient of 0.964. UPV results remained largely unaffected by partial replacement. While biomass ash replacement poses challenges due to strength reduction, it offers advantages for rapid setting and improved resistivity. Future studies should investigate biomass fly ash and mechanical-chemical activation techniques to improve cementitious performance.

Keywords Biomass ash · Electrical resistivity · Hazelnut shell ash · Sugar beet pulp ash · Supplementary cementitious materials

1 Introduction

The world has been getting warmer, and the share of the cement and concrete industry is responsible for 7% of annual CO_2 emissions [1]. One of the most effective strategies for reducing the environmental impact of cement and concrete is partially substituting cement with another material [2]. For decades, industrial by-products such as fly ash, ground granulated blast furnace slag, and silica fume have been used as supplementary cementitious materials (SCMs), with their usage specified in various standards [3].

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The search for alternative SCMs has become a widely discussed topic [4]. Every production produces waste to some extent. Industrial wastes produced in large quantities are promising candidates in this context, including waste glass powder [5, 6], steel slag [7], red mud [8], municipal solid waste incineration ash [9], and agricultural by-products such as rice husk ash [10, 11], palm oil fuel ash [12], wood waste ash [13], corn cob ash [14], and bagasse ash [15]. Agricultural wastes present a twofold perspective: on one hand, their generation during agricultural production poses a management challenge; on the other hand, they offer an opportunity for up-cycling and viable further use scenarios. Numerous studies have focused on recycling and upcycling agricultural wastes, with biomass fuels emerging as one of the most promising waste management strategies [16]. This approach not only addresses waste management but also offers multiple value-added applications. Biomass can be utilized for energy production through various methods, including incineration [17]. However, this process presents an additional challenge: the management of biomass ash residue. As the use of biomass, alongside other renewable energy sources, continues to gain prominence in the context of sustainable development, addressing the effective utilization or disposal of biomass ash has become a critical consideration.

Türkiye produces two-third of the total hazelnuts around the world. In Türkiye, a significant portion of hazelnuts is exported after being unshelled, resulting in a substantial accumulation of hazelnut shells as a byproduct. For decades, these shells have been utilized as a fuel source for household heating and bakeries, either in their raw form or as pellets. Studies indicate that hazelnut shells possess a high calorific value, ranging from 4200 to 4500 kcal/kg, which outperforms that of lignite [18–20]. This indicates that hazelnut shells have the potential to be utilized as a solid biomass fuel in thermal power plants for the production of electrical energy. Several studies in Türkiye have focused on evaluating the viability of using hazelnut shells as a biomass energy source [18, 19, 21–23]. Such approach represents a more sustainable and environmentally conscious alternative. This practice can be considered sustainable, as the carbon emissions from biomass combustion are regarded as neutral, provided that the biomass is replanted [24]. However, this process generates a significant amount of bottom ash, specifically hazelnut shell ash. In contrast to the numerous studies exploring the potential for energy production from biomass in Türkiye, there is a limited body of research on the valorization of hazelnut shell ash in concrete. In developing countries such as Türkiye, the demand for construction materials is continually growing, highlighting the potential for utilizing waste materials and by-products in the construction industry [7]. The ash generated from biomass combustion amounts to nearly 500 Mt per year [25]. Given the scale of the construction industry, it presents a significant opportunity to utilize such waste materials on a large scale, and in some cases, may be the only viable option for managing the waste [26].

Baran et al. [27] investigated the effects of incorporating hazelnut shell ash into cement. The particle size of the ash was smaller than 0.150 mm. Their study revealed that the hazelnut shell ash primarily consists of alite, combeite, and wadeite compounds. The authors blended Ordinary Portland Cement with hazelnut shell ash in varying proportions, ranging from 5% to 30% in 5% intervals. Their findings indicated that as the replacement rate increased, the content of equivalent Na_2O and K_2O also increased, while the levels of SiO_2, Fe_2O_3, Al_2O_3, and CaO oxides decreased. Notably, the inclusion of hazelnut shell ash led to a significant acceleration in setting times, with the initial setting time reduced by 96% and the final setting time reduced by 84% at a 30% replacement rate. The authors attributed this phenomenon to the formation of calcium langbeinite, due to the high alkali content of the hazelnut shell ash. Moreover, while replacing cement with hazelnut shell ash resulted in an increase in expansion, it remained within the acceptable limit of 10 mm as specified by EN 197-1. However, compressive strength decreased with higher replacement rates, with the reduction becoming more evident after a 10% replacement rate. Nevertheless, up to a 5% replacement rate, the compressive strength values remained acceptable.

Ozocak & Sisman [28] investigated the pozzolanic potential of hazelnut shell ash, which was obtained by combusting hazelnut shells directly in a furnace. The analysis revealed that hazelnut shell ash contains 39.91% SiO_2, 23.71% Fe_2O_3, 7.83% Al_2O_3, 5.42% K_2O, 7.2% MgO, and 1.9% CaO. Their study indicates that hazelnut shell ash has relatively low alkali content but is rich in silica and alumina, a finding that diverges from existing literature. The authors used 5% to 20% replacement rates in 5% increments. Their results showed that the specific weight of concrete samples decreased with increasing replacement rates while water absorption increased. Also, thermal conductivity decreased by 41.48%. The authors attributed both the reduction in thermal conductivity and the increase in water absorption to the higher void content in the concrete samples incorporated with hazelnut shell ash. Additionally, the 90-day compressive strength decreased as the replacement rate increased. Based on these findings, the authors recommended that up to a 10% replacement rate is viable for producing structural concrete.

There are many studies on the usability of sugar cane bagasse ash as a partial replacement for cement [29]. However, there are very few studies on the potential of sugar beet pulp ash [30–32]. Sugar beet is more commonly found in colder

regions due to its resistance to harsh conditions, whereas sugar cane thrives in warmer or tropical climates [33]. Türkiye is ranked fifth place in sugar beet production around the world [34]. Currently, 33 sugar factories are operating in Türkiye, all of which process sugar beet. Following peeling, sugar beet pulp is wet. Once dried, it can be pelleted or left in bulk, primarily for use as animal feed. However, if the ash from sugar beet possesses potential as a substitute for cement, since it already has a potential to be a solid biomass energy source, using it as animal feed would be considered downcycling.

Biomasses are utilized in combustion processes for more advanced applications, such as energy production, resulting in the generation of biomass ash [35]. Due to their vast availability in Türkiye, both hazelnut shell ash and sugar beet pulp ash possess significant potential as partial substitutes for cement. If not utilized in this industry, they would otherwise become waste or low-value products. The construction industry, with its ever-growing demand, presents an ideal sector for incorporating these materials, offering both environmental and economic benefits. The performance of cement mortars incorporating biomass ash as SCM can be assessed using both destructive and non-destructive tests. Non-destructive testing methods for concrete have been a prominent topic of research for decades. Ultrasonic pulse velocity is one of the most widely used methods, as it is practical and provides valuable insight into the internal structure of concrete. Additionally, it enables the calculation of dynamic elastic modulus. Another widely utilized non-destructive testing method is resistivity, which is commonly employed to assess the electron-carrying capacity of concrete. Resistivity serves as an indicator of micropore connectivity and a measure of the quality and durability of concrete [36].

While various biomass ashes have been studied for their performance as SCMs, research on hazelnut shell ash and sugar beet pulp ash remains limited. In particular, the effect of biomass bottom ash on the electrical resistivity of cement mortars has received little attention, especially using alternative measurement techniques. This study introduces a novel DC-based resistivity method and provides a detailed evaluation of biomass ash incorporation in cementitious composites, offering new data on its potential as a sustainable cement replacement.

2 Materials and methods

Two biomass ashes were used and incorporated with cement at replacement rates of 5%, 10%, and 15% by weight, and there is a control mix without any replacement. The biomass ashes used here are hazelnut shell ash, and sugar beet pulp ash (Fig. 1). Hazelnut shell ash has a brown colour, while sugar beet pulp ash has light grey colour.

Hazelnut shell ash was obtained from a local bakery in Türkiye, which operates two ovens, one of which is solely fueled by hazelnut shells (Fig. 2).

Sugar beet pulps have been combusted in a handmade open-air oven. The ash residue went down through the grills. 300 μm sieve was used to eliminate unburnt particles.

2.1 Physical and chemical properties

CEM I 42.R Marmara Cement, which satisfies EN 197-1, was used for the production of cement mortars. Mean particle size (D_{50}) of the cement is measured as 13.56 μm. BET analysis is conducted on both hazelnut shell ash and sugar beet pulp ash. BET surface area of sugar beet pulp ash is found 2.51932 m^2/g, and of hazelnut shell ash is 3.93437 m^2/g. XRF results are presented in Table 1.

XRD analysis was also conducted on both of the materials with Bruker D8 Advance model equipment. XRD curves for both sugar beet pulp ash and hazelnut shell ash are presented in Fig. 3 and 4, respectively.

For the sugar beet pulp ash, the peak at 29.4^o is identified as $CaCO_3$. The peak at 24.32^o is identified as anhydrite ($CaSO_4$). The peak at 26.71^o is identified as quartz. Also, there are peaks of arcanite, periclase (MgO), and sylvite. The XRD curve of sugar beet pulp ash implies that the material in the subject is calcium (and potassium to some extent) rich biomass. According to the XRD data, amorphous silica content is low. However, the ash contains high amount of calcium, which may lead to self-cementing.

For the hazelnut shell ash, the peaks at 36.1^o and 39.5^o are identified as periclase and sylvite, respectively. The peak at 26.9^o is identified as quartz (SiO_2). The peak at 29.30^o is most likely calcite. Another peak at 31.3^o is detected as wollastonite ($CaSiO_3$), which is common in calcium-rich biomass ash.

The specific gravity values of the materials are determined as per EN 196-3 and as follows: hazelnut shell ash (2.33), sugar beet pulp ash (2.66), and cement (3.03). Mean particle size of hazelnut shell ash is 57.65 μm. The particle sizes have been determined by Bettersize BT-2001 Laser Particle Size Analyzer. The mean particle size (D_{50}) of sugar beet pulp ash



Fig. 1 Hazelnut shell ash (top) and sugar beet pulp ash (bottom)



Fig. 2 Hazelnut shells as fuel

is determined to be 11.63 μm, which is finer than the cement. Particle size distributions of cement, hazelnut shell ash and sugar beet pulp ash are presented in Fig. 5.

The finer particle size of sugar beet pulp ash (D_{50} = 11.63 μm) compared to hazelnut shell ash (D_{50} = 57.65 μm) may promote improved particle packing, which is generally associated with improved mechanical performance in cement mortars [37, 38]. This significant difference between the median particle sizes suggests that sugar beet pulp ash is more capable of filling voids between cement grains, which could influence packing density and water demand. The D_{10}, D_{25}, D_{50}, D_{75} and D_{90} values for sugar beet pulp ash were 1.897 μm, 4.187 μm, 11.63 μm, 34.16 μm, and 71.62 μm, respectively. In contrast, hazelnut shell ash showed a coarser profile, with corresponding values of 8.715 μm, 22.52 μm, 57.65 μm, 115.7

Table 1 XRF analysis of biomass ashes (%)

Compound	Hazelnut shell ash	Sugar beet pulp ash
CaO	44.17	40.50
Al_2O_3	1.27	2.02
Fe_2O_3	0.90	1.57
SiO_2	3.45	7.83
MgO	7.92	15.41
K_2O	10.02	11.26
P_2O_5	4.52	4.58
SO_3	0.94	8.33
Na_2O	0.01	2.11
Cl	0.24	0.41

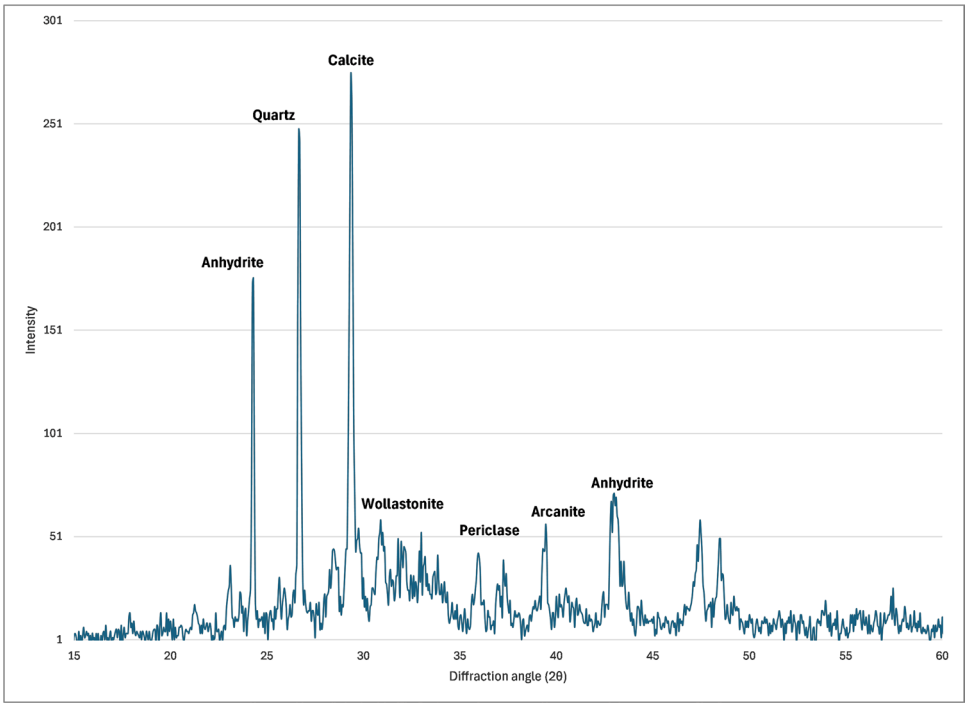


Fig. 3 XRD curve of sugar beet pulp ash

μm, and 185.1 μm. According to the findings, sugar beet pulp ash exhibited a narrower and finer distribution compared to hazelnut shell ash. This finer particle size of sugar beet pulp ash implies a potentially denser particle packing, which can contribute to a better mechanical performance. The wider distribution and larger median size of hazelnut shell ash can result in increased void content and reduced packing efficiency, and inevitably, poorer mechanical performance.

2.2 Mix design

The water/binder ratio has been determined to be 0.5. The replacement rate of hazelnut shell ash and sugar beet pulp ash were 5%, 10%, and 15% by weight. Standard sand that satisfies EN 196-1 was used for all the mixtures. The cement-to-sand ratio is 1:3. The mixture design is presented in Table 2.

The specimens are produced as per ASTM C305-20 [39]. The mix is placed into 4 cm x 4 cm x 16 cm moulds for flexural strength as per ASTM C348-21 [40] and compressive strength as per ASTM C349-24 [41], which are removed 3 days after the mix is prepared. Then, the specimens are placed into a plastic sealed bag for 28 days and 90 days, at 25 °C.

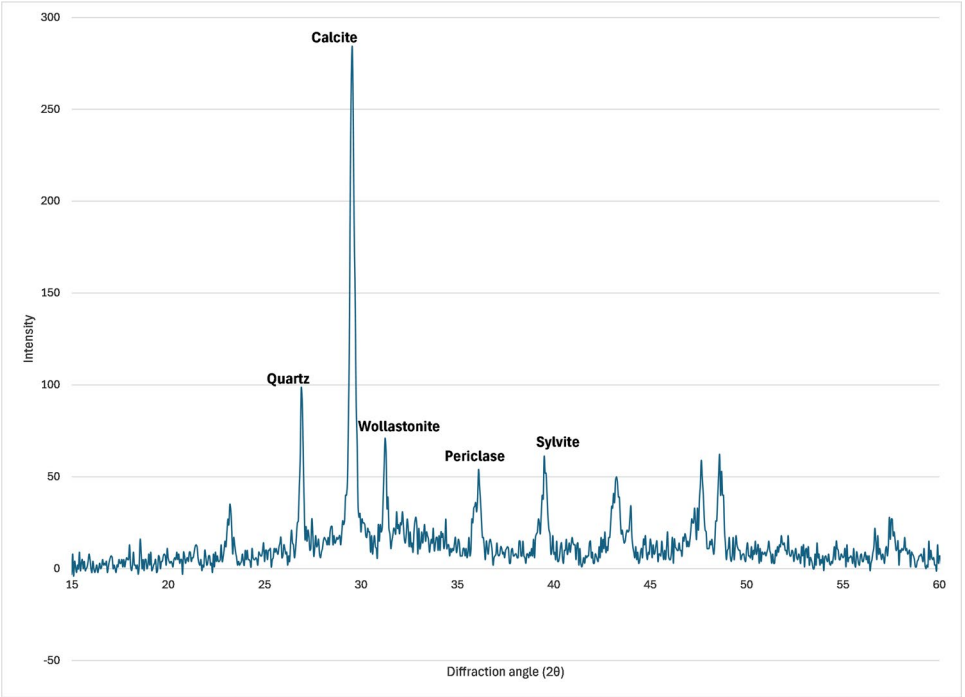


Fig. 4 XRD curve of hazelnut shell ash

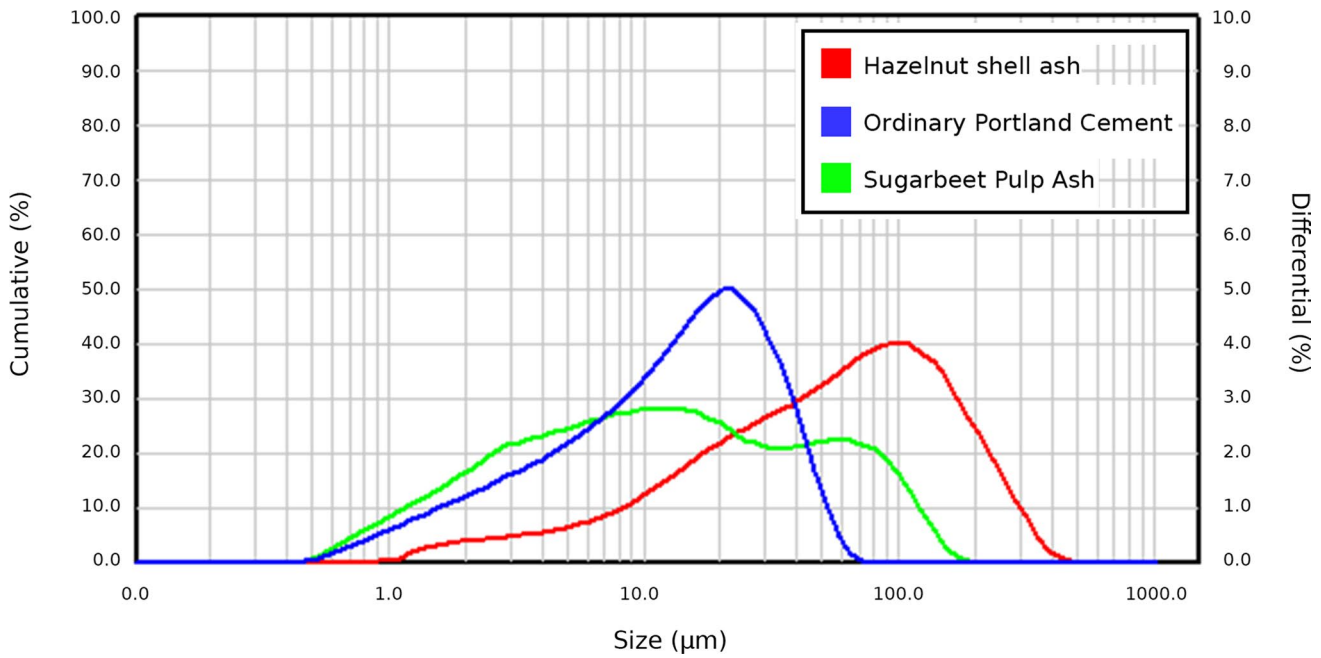


Fig. 5 Particle size distributions

2.3 Setting time

The effects of hazelnut shell ash and sugar beet pulp ash replacement on both initial and final setting time have been determined as per EN 196-3 [42]. Vector Vicatron X12 model equipment was used to determine the setting time. 500 gr of cement was used to determine normal consistency. Cement was partially replaced with hazelnut shell ash and sugar beet pulp ash by 5%, 10%, and 15%. Initial and final setting times for both materials are presented in Table 3.

Table 2 Mix design

Mixture	Cement (g)	Water (ml)	Sugar beet pulp ash (g)	Hazelnut shell ash (g)	Sand (g)
CONTROL	450.0	225	–	–	1350
SBPA_5	427.5	225	22.5	–	1350
SBPA_10	405.0	225	45.0	–	1350
SBPA_15	382.5	225	67.5	–	1350
HSA_5	427.5	225	–	22.5	1350
HSA_10	405.0	225	–	45.0	1350
HSA_15	382.5	225	–	67.5	1350

Table 3 Initial and final setting time

Material	Water demand (%)	Initial setting time (min)	Final setting time (min)
OPC_0	30.0	133	188
SBPA_5	30.7	223	315
SBPA_10	32.2	256	350
SBPA_15	34.7	279	374
HSA_5	31.6	180	300
HSA_10	30.8	90	130
HSA_15	30.6	70	115

2.4 Compressive strength and flexural strength

Compressive and flexural strength tests were conducted at 28 and 90 days on three specimens for each age. The specimens were cured in a moist environment under ambient conditions until testing. Compressive strength was determined using a 250 kN load capacity compressive pressure machine, while flexural strength was measured with a 15 kN load capacity flexural pressure machine. Both devices directly display the respective strength values in megapascals (MPa). The tests have been conducted in accordance with ASTM 349-24 and ASTM C348-21, respectively.

2.5 Ultrasonic pulse velocity

Ultrasonic pulse velocity (UPV) is measured with Controls 58-E4800 device, in compliance with ASTM C597-22 [43]. The device has a calibration bar, which should display precisely 57.3 μ.sec when measured. UPV measurements were performed on 4 x 4 x 16 cm specimens along their 16 cm length using the direct transmission method. The device displays a velocity in μ.sec. Then, the measurements were converted into m/s [44].

2.6 Electrical resistivity

Resistivity measurements are based on the fact that the voltage changes due to an applied current [45]. Measurement of resistivity of concrete is based on Ohm's law (Eq. 1), where V is voltage, I is current, and R is resistance:

$$V = I * R \tag{1}$$

Resistivity measurement methods vary based on the type of current (alternating current or direct current), the number of probes (two-probe bulk resistivity or four-probe Wenner array surface resistivity) [46], and specifications such as ASTM C1876-19 or AASHTO T358, which are not strictly limiting. In electrical resistivity measurements of concrete, the applied current can be either alternating current (AC) or direct current (DC), each of which influences the results differently [46].



Fig. 6 Four probe Wenner method resistivity meter



Fig. 7 Calibration of resistivity meter

AC is more widely suggested, since the dipoles of ions in the pore solution position themselves in a way that directs the current [47, 48].

The electrical resistivity of the cement mortar specimens was measured using two methods in this study: the four-probe Wenner method, which employs an AC measurement technique, and an insulation resistance tester, an experimental DC-based technique integrated with a four-probe configuration. Electrical resistivity was measured at 90 days to assess performance at later curing ages.

2.6.1 Four probe Wenner method

The Wenner method consists of measuring the electrical resistivity through the contact of four probes with the specimen, where the outer probes apply an electric current (I) and the inner probes measure the potential difference (V). The test was conducted using a device that applies a minimal AC current through outer probes and measures the voltage with inner probes. An image of the device is provided in Fig. 6. The device also includes a calibration circuit, which outputs a value of 23 Ω·m (Fig. 7). To ensure proper conductivity in the probes, wet sponges are placed inside. The device is firmly placed on the surface, and it then displays the electrical resistivity value in Ω·m. The probe spacing is 35 mm.

2.6.2 Measuring by using insulation resistance tester

DC-based techniques may be affected by high polarization effects at the electrode-surface interface [49]. Polarization causes the measured electrical resistivity to increase over time, making it unstable. DC-based measurements should be completed within a short duration to overcome this pitfall, as polarization effects remain insignificant if the measurement is completed within 10 s [49, 50]. This study compares two different resistivity methods, one based on the application of AC, while the other is based on DC, and an insulation resistance tester, also known as a megohmmeter. Yurt et al. [51] employed an insulation resistance tester to evaluate the resistance of alkali-activated composites at a voltage of 1000 V. Their setup included two probes. While the authors presented measured resistance rather than resistivity, the results appear to be correlated with compressive strength measurements.

A Fluke 1507 insulation resistance tester, which can perform insulation tests from 0.01 MΩ to 10 GΩ, was used to measure resistivity [52]. The device was used in conjunction with the four-probe method, which is recommended to minimize the influence of contact surface effects [46]. The outer probes of the tester were connected to the insulation

resistance tester, while the inner probes were connected to a multimeter to measure voltage. The tester was set to operate at 100 V. However, the actual voltage supplied to the specimen varies depending on the specimen, even if the tester is set to a fixed voltage.

The insulation resistance tester applies a current, prints the applied voltage and measures resistance in accordance with Ohm's law. The resistivity calculation follows the standard four-probe method with a slight modification. The test setup can be seen in Fig. 8.

The insulation resistance tester's probes are attached to the outer probes, while a multimeter that is set to measure voltage between inner probes. The equation 2 is used for resistivity:

$$\rho = 2\pi a \frac{V_{\text{multimeter}}}{\frac{V_{\text{ins}}}{R_{\text{ins}}}} \tag{2}$$

Here, $V_{\text{multimeter}}$ is the voltage measured by the inner probes, V_{ins} is the voltage displayed on the insulation resistance tester, and R_{ins} is the resistance reading from the tester. a represents the probe spacing. Probe spacing for resistivity measurements is related to the measured specimen sizes. It is suggested to use 35 mm probe spacing for the specimens with 160 mm length [53]. This calculation yields the resistivity value of the specimen, in the unit of Ω.m.

3 Results and analysis

3.1 Compressive strength

Both 28 days and 90 days compressive strength of 5%, 10%, and 15% replacement of cement by sugar beet pulp ash and hazelnut shell ash are presented in Fig. 9.

Inclusion of biomass ash caused a decrease in compressive strength at both 28 and 90 days, as can be seen in Fig. 9. The decrease in compressive strength of hazelnut shell ash incorporated cement mortars is more evident. The 28-day compressive strength was measured to be 50.9 MPa at 0% replacement rate. And the 28-day compressive strength has decreased to 33.7 MPa even at 5% hazelnut shell ash replacement rate, and at 15% hazelnut shell ash replacement rate, the decrease is even greater, 26.3 MPa. The 90-day compressive strength was measured to be 66.1 MPa at 0% replacement rate. The 90-day compressive strength values decreased to 32.1 MPa at the highest hazelnut shell ash replacement rate, which is more than half decline. And the decrease in compressive strength increased as the replacement rate increased.

On the other hand, although there is still a decrease in the compressive strength of sugar beet pulp ash-incorporated cement mortar, this decrease is less than that of hazelnut shell ash-incorporated cement mortar. The 28-day compressive strength has decreased to 46.2 MPa, with a difference of only 4.7 MPa. However, as the replacement rate increases, a greater decrease in 28-day compressive strength was observed, up to 12.7 MPa. The 90 days compressive strength has decreased by 9.5 MPa at 5% replacement rate. The same phenomenon, inverse relationship between replacement rate

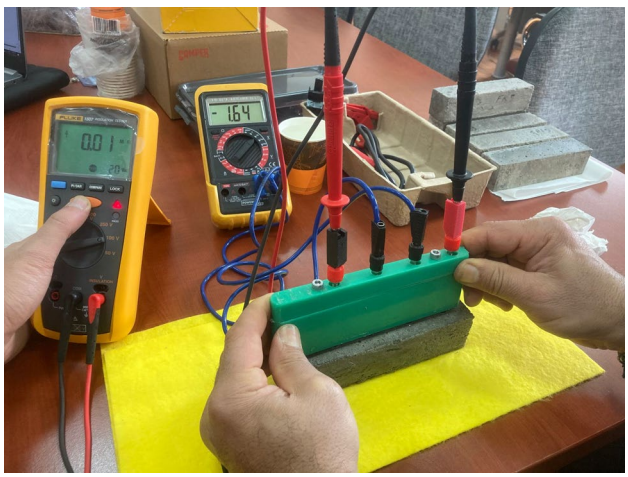


Fig. 8 Insulation resistance tester setup

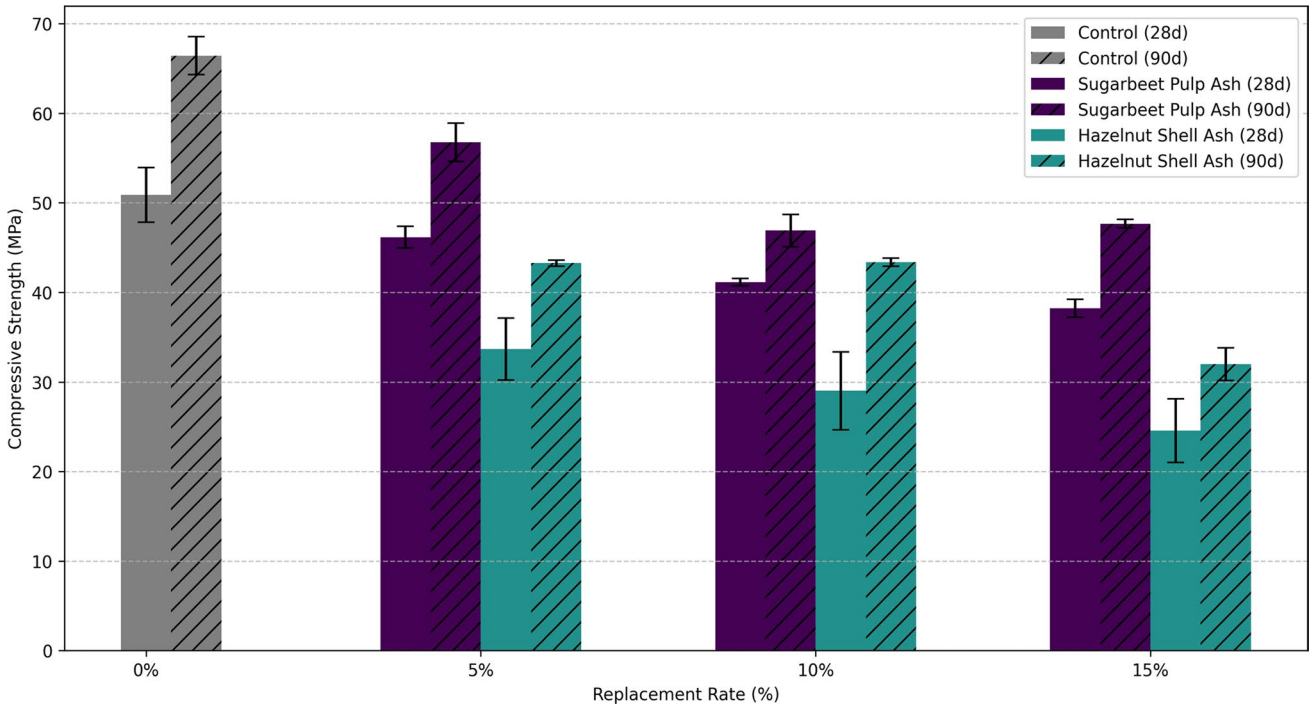


Fig. 9 28 days and 90 days compressive strength (MPa)

and compressive strength, is applicable to 90 days compressive strength. The decrease in 90-day compressive strength for sugar beet pulp ash incorporated mortars are 19.2 MPa and 18.1 MPa at 10% and 15%, respectively.

Possible reasons for the decrease in compressive strength include the dilution effect, low pozzolanic activity due to low SiO_2 and Al_2O_3 content, insufficient particle packing caused by coarse particle size, and differences in water absorption between the materials. The observed reduction in compressive strength upon partial replacement of cement can be attributed to the dilution effect, where the decreased cement content reduces the amount of available binders for hydration, ultimately leading to lower strength development [54]. Such a decrease in compressive strength can also be attributed to the low pozzolanic activity due to the low SiO_2 and Al_2O_3 content, which has also been reported in other studies involving biomass-based materials [55]. However, the SiO_2 and Al_2O_3 contents of both sugar beet pulp ash and hazelnut shell ash are similar and do not appear enough to explain the difference in the measured compressive strength values between the two biomass ashes (Table 1). The difference in compressive strength between cement mortars incorporating sugar beet bagasse ash and those incorporating hazelnut shell ash can be attributed to the differences in the physical properties of the materials. The BET surface area of hazelnut shell ash is significantly higher than that of sugar beet bagasse ash (3.93437 m^2/g and 2.51932 m^2/g, respectively); however, its particle size is coarser in comparison (Fig. 5). While the higher surface area may suggest greater reactivity potential [56], the coarse particle size can hinder effective particle packing and reduce the filler effect [57]. Sugar beet bagasse ash has a finer particle size distribution, which may enhance particle packing and densifies the matrix, ultimately resulting in better compressive strength performance compared to hazelnut shell ash [57].

3.2 Flexural strength

Both the 28-day and 90-day flexural strengths for cement replacement levels of 5%, 10%, and 15% using sugar beet pulp ash and hazelnut shell ash are presented in Fig. 10.

The inclusion of hazelnut shell ash led to a reduction in flexural strength at 28 days, decreasing from 7.7 MPa (control) to a range of 6.1 MPa to 4.9 MPa across increasing replacement rates. In contrast, sugar beet pulp ash caused a smaller decrease, with flexural strength ranging from 7.3 MPa to 6.8 MPa. At 90 days, hazelnut shell ash showed little to no improvement in flexural strength compared to 28-day results. However, sugar beet pulp ash at a 5% replacement rate reached 8.1 MPa at 90 days, and reached a flexural strength 0.6 MPa higher than the control. This improvement can be attributed to the fine particle size of sugar beet pulp ash, which enhanced particle packing and contributed to the formation of a denser microstructure [58].

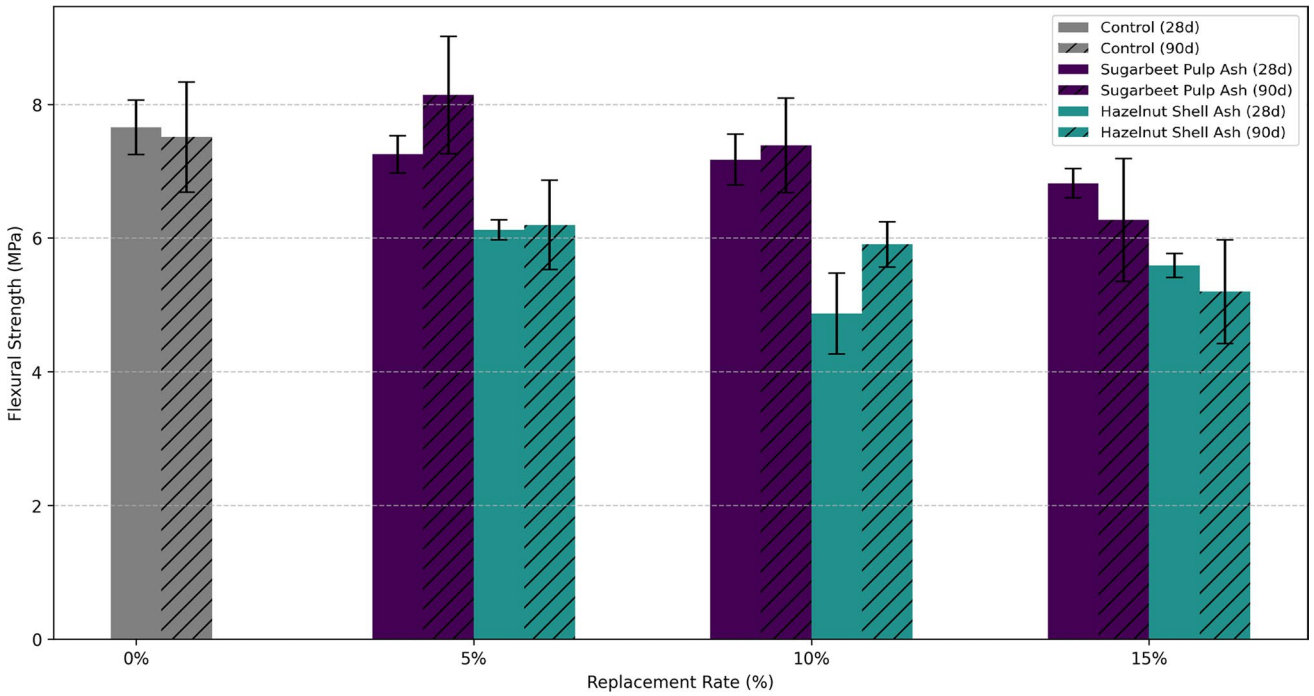


Fig. 10 28 days and 90 days flexural strength (MPa)

However, at higher replacement levels, particularly at 15%, a reduction in flexural strength was observed. A similar trend has been reported for high fly ash replacement levels [59], which may be associated with the dilution effect, where the reduced cement content is insufficient to ensure adequate bonding and strength development.

In contrast, for hazelnut shell ash replacement, the decline in flexural strength was evident even at the 5% replacement level, and the decline became more pronounced with higher replacement rates. Such decrease may be attributed to the material's low pozzolanic activity and relatively coarse particle size, which likely hindered its contribution to a denser cementitious matrix and ended up with greater porosity.

3.3 Ultrasonic pulse velocity

Both the 28-day and 90-day UPV for cement replacement levels of 5%, 10%, and 15% using sugar beet pulp ash and hazelnut shell ash are presented in Fig. 11.

UPV is often influenced by the material's density, elasticity, and internal structure, and usually correlated with strength [60]. UPV results tend to decrease with increasing replacement levels; however, the reduction is relatively small. For hazelnut shell ash replacement, the most pronounced decrease is observed at the 15% replacement level. Although UPV results at 28 and 90 days exhibit a strong correlation with compressive strength, this correlation is weaker for flexural strength. The correlation between flexural strength and UPV is usually not as strong as compressive strength and UPV [61]. Under flexural stress, microcracks penetrate each other to form larger cracks [62]. Such localized flaws that lead to fracture may not be detected by UPV, however, they can effect negatively the flexural strength and disrupt the correlation between UPV and flexural strength. Another reason for this discrepancy is that UPV primarily evaluates the bulk properties of the material rather than surface characteristics or the distribution of microcracks, which play a crucial role in flexural strength development [63].

3.4 Electrical resistivity

3.4.1 Four probe Wenner method

The electrical resistivity that was measured by four probe Wenner method is presented in Fig. 12. Usually, compressive strength and UPV are correlated with electrical resistivity. However, in this study, hazelnut shell incorporated cement

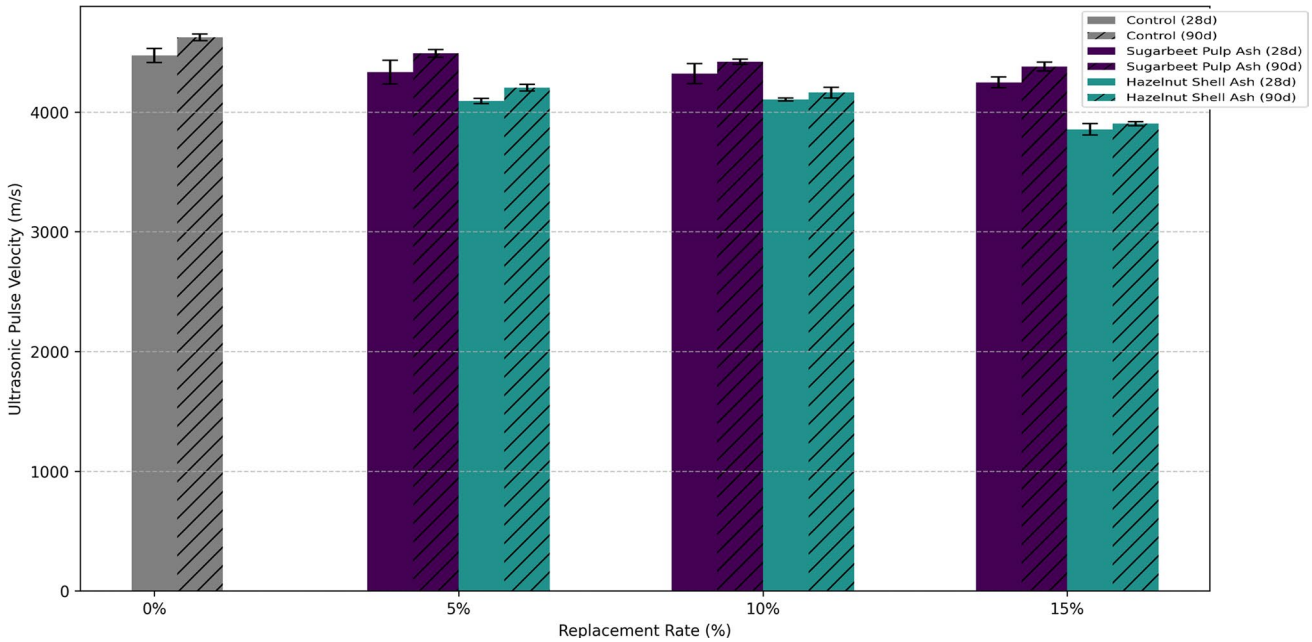


Fig. 11 28 days and 90 days ultrasonic pulse velocity (m/s)

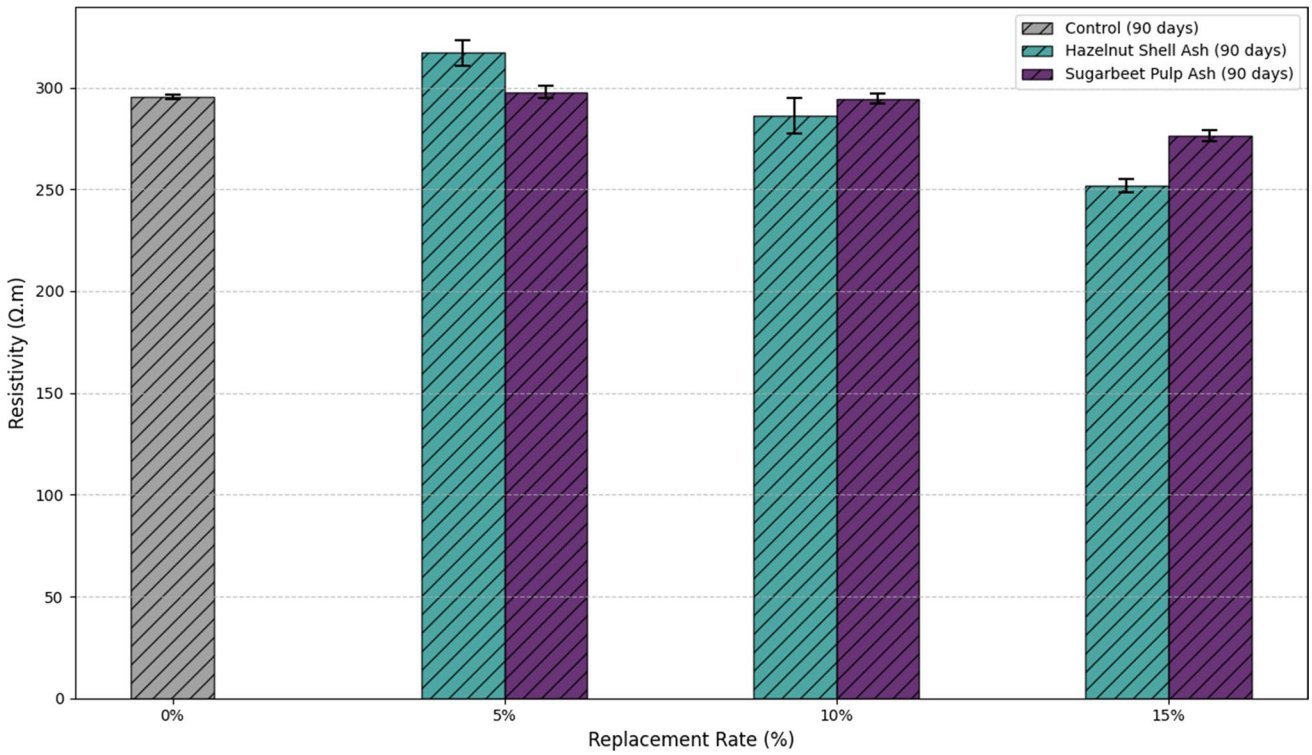


Fig. 12 90 days electrical resistivity measurement by using four probe Wenner method

mortars perform as good as the cement mortars without any replacement. This can be attributed with either unreliable nature of electrical resistivity methods, or, hazelnut shell ashes did not react with hydration products, but they acted as a filler. Another explanation can be hazelnut shell ashes did not react, and they agglomerated at the surface, and this led to a higher surface resistivity. Electrical resistivity was decreased by increasing replacement rate, which can be attributed with bigger internal voids inside as more cement is replaced. In the sugar beet pulp ash, the performance at

5% and 10% seems closer. And there is a decrease at 15% replacement rate. This result can be attributed with smaller particle size of sugar beet pulp ash.

3.4.2 Measuring by using insulation resistance tester

The results are presented in Fig. 13. Resistivity was calculated through Eq. 2. The main limitation of this measurement method is the range of the insulation test, which spans from 0.01 MΩ to 10 GΩ. For most measurements, the resistance was recorded as 0.01 MΩ or 0.02 MΩ, which falls within the lowest range. Due to the low sensitivity of the measurement, the results lack precision to some extent. To overcome this shortcoming, and determine the injected current during concrete resistivity measurements using the insulation resistance tester, a statistical analysis was conducted on multiple calculated current values. The insulation resistance tester does not directly measure current, however, it displays both resistance and voltage, from which the current was derived using Ohm's Law. A series of 21 current values were computed by dividing the displayed voltage by the corresponding resistance readings (Table 4).

A statistical analysis included computing the mean, standard deviation, coefficient of variation (CV %), and a 95% confidence interval (CI). The key statistical results presented that the mean current was 0.00200 A, with a standard deviation of 0.00022 A and a coefficient of variation of 11%. The 95% confidence interval ranged from 0.00190 A to 0.00210 A. The calculated mean current, with low variability and a confidence interval including 0.002 A, demonstrates strong statistical consistency. Given these findings and considering the precision limit of resistance measurement of the testing device, it is reasonable to assume that the injected current is 0.002 A for all further analysis of concrete resistivity measurements. The one-sample t-test yielded a t-statistic of 0.049 and a p-value of 0.961, indicating no statistically significant difference between the measured data and the assumed value of 0.002 A. Due to this fact, the injected current is considered 0.002 A for all measurements.

A trend is clearly observable when considering the standard deviations: resistivity decreases as the replacement rate increases. Such devices are not primarily designed for measuring the resistivity of concrete, but rather for measuring insulation at a safe voltage level. However, some studies have utilized similar devices [51], and since they apply high voltage and low current, they may be suitable for practical resistivity measurements, especially as they appear to minimize polarization effects.

Table 4 Voltage and resistance readings, and calculated current

Displayed voltage (V)	Displayed resistance (Ω)	Calculated current (A)
21	10000	0.00210
22	10000	0.00220
20	10000	0.00200
21	10000	0.00210
22	10000	0.00220
21	10000	0.00210
22	10000	0.00220
22	10000	0.00220
21	10000	0.00210
19	10000	0.00190
20	10000	0.00200
20	10000	0.00200
21	10000	0.00210
25	20000	0.00125
23	10000	0.00230
20	10000	0.00200
19	10000	0.00190
19	10000	0.00190
18	10000	0.00180
19	10000	0.00190
18	10000	0.00180

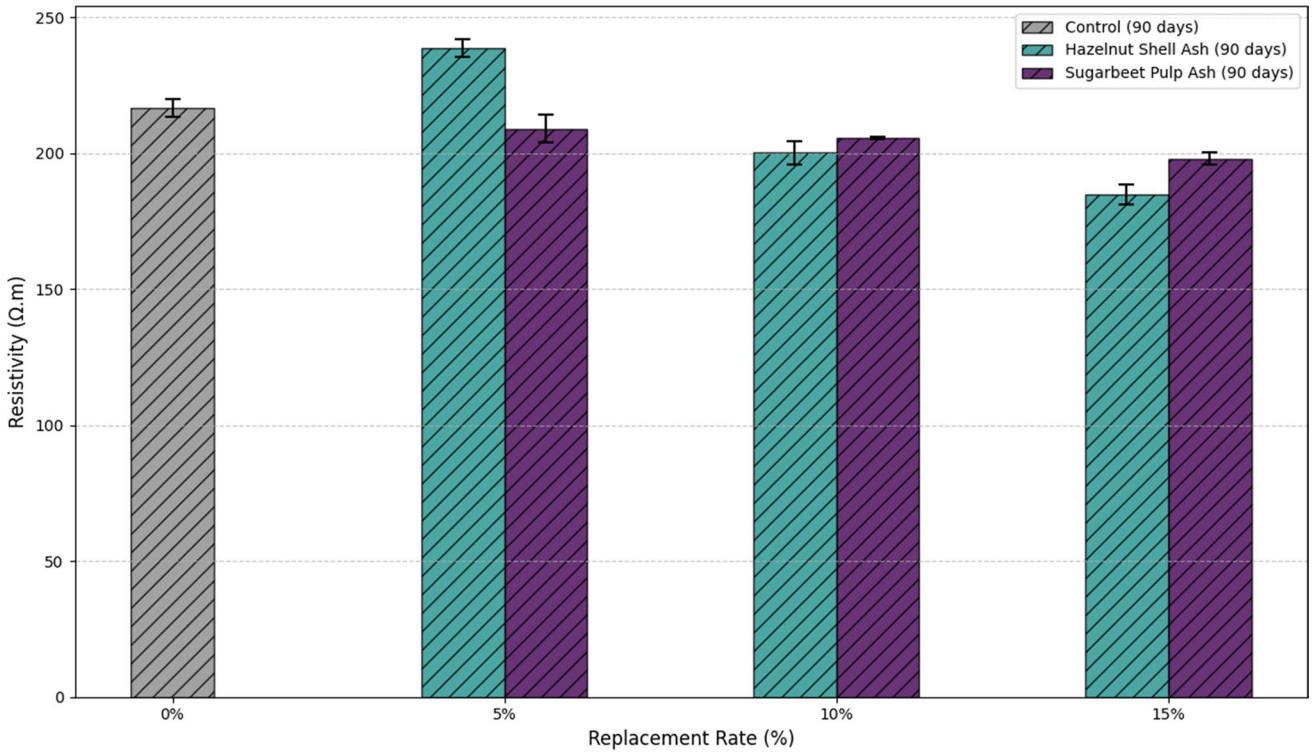
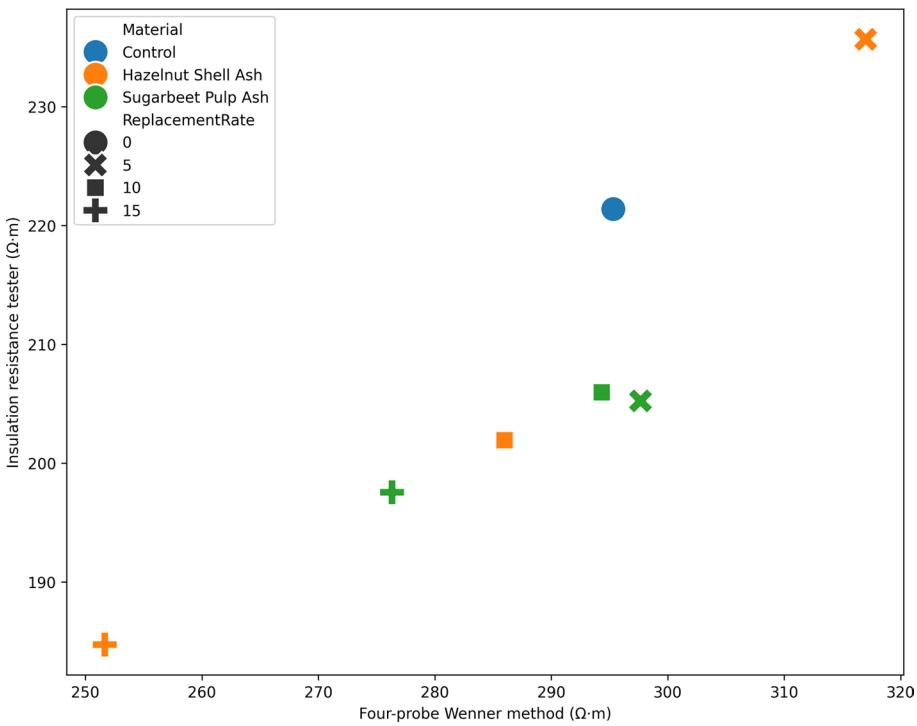


Fig. 13 90 days electrical resistivity measurement by using insulation resistance tester

A comparison between two different resistivity measurement methods was conducted, revealing a correlation between both techniques (Fig. 14). Although the absolute values differ, the overall trends remain consistent. The resistivity values measured using the insulation resistance tester appear lower than those obtained via the four-probe Wenner method. This discrepancy may sourced from the limited sensitivity of the insulation resistance tester, which measures resistance

Fig. 14 90 days electrical resistivity measurement by using insulation resistance tester



within a range of 0.01 MΩ–10 GΩ. However, given the observed correlation in trends and the novelty of the insulation resistance tester method, this limitation can potentially be addressed with further refinements.

3.5 Correlation between biomass type, replacement rate, compressive strength, flexural strength, electrical resistivity, and ultrasonic pulse velocity

A correlation matrix was generated in IBM SPSS Statistics to explore relationships between variables. The analysis uses Spearman's rank-order correlation coefficient, a non-parametric measure that quantifies the strength and direction of monotonic associations (whether variables increase or decrease together, even if not linearly) between pairs of variables. Spearman's coefficient ranges from – 1 to 1, where values close to 1 indicate a strong positive monotonic relationship (both variables trend in the same direction), values near – 1 suggest a strong inverse monotonic relationship (one variable increases while the other decreases), and values around 0 imply no consistent directional relationship. For example, a coefficient of 0.929 between compressive strength and ultrasonic pulse velocity at 28 days would indicate that higher ultrasonic pulse velocity consistently aligns with greater compressive strength, even if the relationship is not strictly linear. This matrix helps identify key drivers of material performance, such as whether hazelnut shell ash or sugar beet pulp ash replacement rates influence long-term durability, and clarifies how resistivity measurements align across different testing methods. To visualize these correlations, a heatmap was created, where green indicates direct proportionality and red represents inverse proportionality. The intensity of the colors reflects the strength of the correlation, with darker shades indicating stronger relationships (Fig. 15).

The correlation matrix reveals that 28-day compressive strength exhibits a strong correlation with 28-day flexural strength, ultrasonic pulse velocity, and the corresponding 90-day properties, as expected. Additionally, the replacement rate is inversely correlated with all these mechanical and durability properties. An intriguing finding concerns the resistivity measurement methods. While a correlation between the resistivity and 90-day compressive strength, flexural strength, and ultrasonic pulse velocity was anticipated, it is not as strong as expected. However, the four-probe Wenner method and the insulation resistance tester demonstrate a remarkably strong correlation, with a coefficient of 0.964. If only a single method had been used, the validity of the results could have been questioned. Yet, the consistency between the two techniques reinforces the reliability of the findings. Both methods exhibit consistent trends in their

Variable		Replacement Rate	Compressive Strength (28d)	Flexural Strength (28d)	Ultrasonic Pulse Velocity (28d)	Compressive Strength (90d)	Flexural Strength (90d)	Ultrasonic Pulse Velocity (90d)	Four-probe Wenner Method Device (90d)	Insulation Resistance Tester (90d)
Replacement Rate	r	1	-0.641**	-0.523*	-0.538*	-0.584**	-0.59**	-0.646**	-0.863*	-0.918**
	p	.	0.002	0.015	0.012	0.005	0.005	0.002	0.012	0.004
Compressive Strength (28d)	r	-0.641**	1	0.912**	0.929**	0.93**	0.803**	0.959**	0.536	0.571
	p	0.002	.	0	0	0	0	0	0.215	0.18
Flexural Strength (28d)	r	-0.523*	0.912**	1	0.8**	0.831**	0.729**	0.873**	0.393	0.429
	p	0.015	0	.	0	0	0	0	0.383	0.337
Ultrasonic Pulse Velocity (28d)	r	-0.538*	0.929**	0.8**	1	0.91**	0.773**	0.91**	0.321	0.393
	p	0.012	0	0	.	0	0	0	0.482	0.383
Compressive Strength (90d)	r	-0.584**	0.93**	0.831**	0.91**	1	0.658**	0.962**	0.536	0.571
	p	0.005	0	0	0	.	0.001	0	0.215	0.18
Flexural Strength (90d)	r	-0.59**	0.803**	0.729**	0.773**	0.658**	1	0.72**	0.786*	0.75
	p	0.005	0	0	0	0.001	.	0	0.036	0.052
Ultrasonic Pulse Velocity (90d)	r	-0.646**	0.959**	0.873**	0.91**	0.962**	0.72**	1	0.536	0.571
	p	0.002	0	0	0	0	0	.	0.215	0.18
Four-probe Wenner Method Device (90d)	r	-0.863*	0.536	0.393	0.321	0.536	0.786*	0.536	1	0.964**
	p	0.012	0.215	0.383	0.482	0.215	0.036	0.215	.	0
Insulation Resistance Tester (90d)	r	-0.918**	0.571	0.429	0.393	0.571	0.75	0.571	0.964**	1
	p	0.004	0.18	0.337	0.383	0.18	0.052	0.18	0	.

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

Fig. 15 Correlation matrix. ** Correlation is significant at the 0.01 level (2-tailed).* Correlation is significant at the 0.05 level (2-tailed)

results. Resistivity is influenced by multiple factors, including cement type, water-to-cement ratio, aggregate type, pore connectivity, pore solution composition, and the presence of SCM or filler materials [46]. In this study, at a 5% replacement rate, biomass ash appears to have functioned as a non-conductive filler. This observation has been confirmed by two resistivity measurement methods. However, as the replacement rate increases, the internal structure becomes more porous, leading to a decline in resistivity due to the formation of additional internal voids [64].

4 Discussion

One of the most popular research areas today is the identification of locally available alternatives to materials produced through environmentally harmful processes [4]. This study investigates the potential of hazelnut shell and sugar beet pulp as substitutes for cement, a material associated with 7% of entire carbon emissions annually [1]. In addition to its environmental implications, this research is driven by ethical and economic considerations, particularly regarding the combustion of these locally abundant biomasses for energy generation.

Although a comprehensive approach is required to fully assess this potential, the findings of this study offer valuable insights. First, the incorporation of hazelnut shell ash and sugar beet pulp ash led to a decline in the most critical mechanical property of structural concrete, compressive strength, compared to the control mix (50.9 MPa at 28 days and 66.1 MPa at 90 days). This result is attributed to dilution effect [54]. At 28 days, compressive strength decreased by 17.2 to 26.3 MPa (up to 52%) for hazelnut shell ash, and by 4.7 to 12.7 MPa (up to 25%) for sugar beet pulp ash. At 90 days, the observed declines ranged from 22.8 to 34.0 MPa (up to 52%) and from 9.5 to 18.1 MPa (up to 28%), respectively. Such significant decrease is associated with coarser particle size of the hazelnut shell ash (Fig. 5), which hinders particle packing and increases void content, as reflected in higher water demand (Table 3). The decline in compressive strength observed in sugar beet pulp ash-incorporated specimens was less significant, likely thanks to its finer particle size (Fig. 5), which contributed to matrix densification and improved performance compared to hazelnut shell ash [57]. Both materials resulted in lesser strength due to low pozzolanic activity sourced limited SiO_2 and Al_2O_3 content. However, thanks to its smaller particle size and particle packing, sugar beet pulp ash performed relatively better. Also, sugar beet pulp ash has lower surface area, which can be increased by several methods and improve its mechanical performance. This study deliberately minimized additional processing steps to evaluate the raw performance of biomass ash in cementitious composites. For instance, mechanical activation methods (grinding and milling) could be employed to increase the specific surface area of the biomass ashes, potentially enhancing their reactivity and performance in cement-based materials [65–67]. In a study conducted by Chen et al. [68], they achieved to improve the compressive strength of municipal solid waste incineration fly ash incorporated specimens from 35.3 to 56.9 MPa, by using mechanical activation methods. Sugar beet pulp ash is a candidate for similar improvement.

The inclusion of hazelnut shell ash resulted in a serious decrease in both compressive and flexural strength at 28 and 90 days (Figs. 9, 10), yet it accelerated the setting process (Table 3). This suggests that hazelnut shell ash may be suitable for non-structural applications, particularly where rapid setting is advantageous. Additionally, an important finding of this study is the high alkali content of the investigated biomass ashes (Table 1), which indicates their potential suitability for alkali-activated concrete [69]. Given that vast amounts of hazelnut shells and sugar beet pulp are currently downcycled into low-value applications each year, further research is essential to explore their effective utilization in the cement and concrete industry. Effectively utilized, these materials could contribute to more sustainable construction practices. It is well-known that using locally available agricultural wastes such as rice husk ash can lead to decrease in global warming potential [70].

5 Conclusion

Abundant biomass sources in Türkiye, namely hazelnut shell and sugar beet pulp, were examined for their potential as partial cement replacements. Mixtures were prepared with a 0.5 water-to-binder ratio and replacement rates of 5%, 10%, and 15% by weight, resulting valuable findings.

- Türkiye has abundant sources of sugar beet pulp and hazelnut shell, both of which can serve as solid biomass fuels for energy production. This study evaluates the performance of the bottom ash generated from the combustion of these materials without any further mechanical or chemical treatment.

- Hazelnut shell ash replacement resulted in rapid setting compared to mixtures without replacement (Table 3), attributed to its high alkali content (Table 1). In contrast, sugar beet pulp ash caused a delay in setting. The use of hazelnut shell ash may be beneficial for applications requiring rapid setting.
- Both hazelnut shell ash and sugar beet pulp ash replacements led to a decrease in compressive and flexural strength (Figs. 9, 10). The decrease in both compressive strength and flexural strength more evident in hazelnut shell ash incorporated specimens. However, at a 5% replacement rate, specimens incorporating sugar beet pulp ash exhibited only a 4.7 MPa reduction (9.2%) in 28-day compressive strength and a 18.1 MPa reduction (14.5%) in 90-day compressive strength. This result is promising, as additional mechanical activation methods, such as grinding, may further enhance its effectiveness.
- Hazelnut shell ash replacement at a 5% replacement rate resulted in improved electrical resistivity performance, as confirmed by two different resistivity measurement methods (Figs. 12, 13).
- A DC-based electrical resistivity measurement method, utilizing an insulation resistance tester, was tested. The results exhibited a strong correlation with those obtained from the conventional AC-based four-probe Wenner test (Fig. 15). This setup has the potential for further improvement and can be utilized as a resistivity measurement method.
- UPV results were less affected by biomass ash replacement compared to compressive and flexural strength (Fig. 15).
- The biomass ashes used in this study contain a high amount of alkalis, posing a potential risk for alkali-silica reaction. However, this characteristic also makes them suitable for use in alkali-activated concrete, provided they are combined with a highly siliceous material.

As a limitation, the ashes used in this study were obtained from single sources, which may not fully reflect the variability of agricultural wastes. While the 90-day testing period offers valuable insight into later-age performance, it may still be insufficient to fully evaluate long-term durability. Future research should focus on activation methods to mitigate strength loss and enhance mechanical properties (particularly for hazelnut shell ash) and assess long-term durability under realistic exposure conditions. Lastly, only the bottom ash was utilized in this study, leaving the potential applications of biomass-derived fly ash unexplored.

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Data availability Data generated during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare that there is no conflict of interest regarding the publication of this paper.

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