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# Mechanical Performance and Durability of Concrete Containing Rice Husk Ash and Waste Rubber Powder: An Experimental Study with Emphasis on Electrical Resistivity

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**ABSTRACT**

The present study investigates the effects of rice husk ash (RHA) and waste rubber powder (WRP) on the mechanical and durability-related performance of concrete, with particular emphasis on electrical resistivity. Eleven concrete mixtures were prepared with a total cementitious material content of 500 kg/m³, including a control mixture and mixtures incorporating 12% RHA as a cement replacement. Waste rubber powder was used as a partial replacement for sand at 10%, 15%, and 20% by mass, while an air-entraining admixture was used at dosages of 0.1% and 0.2%. Compressive strength and unit weight were measured at 7, 28, and 42 days, while electrical resistivity, water penetration depth under pressure, and water absorption were evaluated at 42 days. The results showed that replacing 12% of the cement with RHA reduced the 42-day compressive strength from 46.5 to 41.6 MPa, while increasing electrical resistivity from 98.3 to 119.5 Ω·m and reducing water penetration depth from 40 to 24.7 mm. The maximum 42-day compressive strength among the rubber-containing mixtures was 29.3 MPa at a 10% rubber replacement level. The effect of rubber replacement on electrical resistivity was non-linear. The mixture containing 12% RHA, 15% waste rubber powder, and 0.1% air-entraining admixture exhibited the highest electrical resistivity among all mixtures, reaching 181.7 Ω·m. The results indicate that the combined use of RHA and waste rubber powder can modify the transport-related properties of concrete, although these benefits may be accompanied by reductions in mechanical strength. These findings highlight the potential of using RHA and waste rubber powder in developing more sustainable concrete while maintaining an appropriate balance between mechanical and transport-related performance.

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## 1. Introduction

The increasing demand for concrete, together with the environmental impacts associated with its constituent materials and the consumption of natural resources, has encouraged the development of more sustainable and resource-efficient concrete technologies. One promising approach is the incorporation of industrial, agricultural, and other waste-derived materials into concrete. In this context, waste rubber powder (WRP) and rice husk ash (RHA) are of particular interest because they can partially replace conventional concrete constituents while potentially modifying both the mechanical and durability-related properties of concrete.

Previous studies have shown that the incorporation of waste rubber can alter the mechanical and durability-related performance of concrete. Jafari et al. [1] investigated concrete containing waste glass and rubber

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under ambient conditions and after exposure to 600 °C. They reported that the addition of rubber and glass reduced compressive strength while increasing tensile strength, and the compressive strength decreased by an average of about 33% after thermal exposure. The mixtures containing 5% rubber with 10% glass powder under ambient conditions and 15% glass powder after thermal exposure showed comparatively better performance, while microstructural observations indicated good bonding between the rubber particles and the concrete paste. Similarly, Jangra et al. [2] reported that replacing fine aggregate with waste rubber crumb in geopolymer concrete reduced compressive strength, with a maximum reduction of about 17% at the highest replacement level; however, the addition of steel fibers partially compensated for this loss and enhanced compressive and flexural strength. Yaghoubi-Nejad and Jahangiri [3] also found that increasing the rubber content generally reduced compressive and flexural strengths, although surface modification of the rubber using silica fume and cementitious coatings could partially improve the bond between rubber particles and cement paste. In addition, the reduction in thermal conductivity with increasing rubber content indicated potential benefits for lightweight concrete and thermal performance. Importantly, the influence of waste rubber is not limited to mechanical properties. Mohseni and Koushk-Baghi [4] observed that increasing the amount of waste rubber crumb reduced mechanical strengths but improved certain durability-related properties. In their study, the chloride-ion diffusion coefficient was reduced by up to 80%, while electrical resistivity increased by up to 87%. These findings indicate that, although rubber incorporation may involve a mechanical-strength penalty, it may simultaneously provide advantages for transport- and durability-related behavior. In a related study, Sidhu and Siddique [5] investigated the use of crumb tire rubber as a partial replacement for coarse aggregate in metakaolin-based high-strength concrete. They reported that increasing the rubber content generally reduced workability, density, compressive strength, splitting tensile strength, and elastic modulus. Nevertheless, an appropriate rubber replacement level could limit the loss of mechanical properties while providing advantages in terms of the deformation behavior of concrete. These findings indicate that the effects of waste rubber depend strongly on the replacement level, rubber characteristics, and properties of the surrounding cementitious matrix.

Rice husk ash is another promising waste-derived material for sustainable concrete. Al-Alwan et al. [6] found that partial replacement of Portland cement with RHA, particularly when finer RHA particles were used, could improve compressive, tensile, and flexural strengths and reduce chloride-ion penetration, whereas increasing the water-to-cement ratio adversely affected concrete performance. Siddika et al. [7], in a review of RHA as a supplementary cementitious material, similarly highlighted its high pozzolanic reactivity and its potential to produce a denser microstructure and improve the mechanical and durability properties of concrete when its fineness and replacement level are appropriately controlled. The electrical resistivity of concrete is also an important parameter in the assessment of durability-related behavior. Ahmadi and Zolghadri [8] showed that electrical resistivity is affected by the water-to-cementitious-materials ratio, the type and composition of pozzolanic materials, their replacement level, and the air content of concrete. Their results identified the water-to-cementitious-materials ratio and pozzolan replacement level among the most influential parameters. In addition, Fallahian and Haddad [9] reported that the use of Taftan natural pozzolan as a partial cement replacement together with an air-entraining agent increased the electrical resistivity of lightweight concrete, suggesting potential benefits for durability-related performance.

Although the available studies provide useful evidence on the individual effects of waste rubber, RHA, pozzolanic materials, and air-entraining admixtures, the combined use of RHA, waste rubber powder, and an air-entraining admixture and its effects on the mechanical and durability-related performance of concrete remain insufficiently documented. In particular, the implications of these materials for the balance between mechanical performance and transport-related properties require further experimental investigation. Therefore, the present study experimentally investigates the effects of RHA, waste rubber powder, and an air-entraining admixture on the performance of concrete, with particular emphasis on electrical resistivity and water transport. Compressive strength, water penetration under pressure, water absorption, and unit weight are also evaluated to provide a comprehensive assessment of the effects of incorporating these materials. By considering these properties together, the study aims to clarify the extent to which the use of RHA and waste rubber powder can modify the mechanical and transport-related performance of concrete and to identify mixture compositions that provide an appropriate balance between these properties.

## 2. Theoretical Background of the Study

The mechanical and durability-related performance of concrete is governed by the characteristics of the cement paste, aggregates, interfacial transition zone (ITZ), and pore structure of the cementitious matrix. Modification of the concrete constituents can alter these characteristics and consequently affect strength, water transport, electrical resistivity, and density. This issue is particularly important when agricultural and industrial waste materials are incorporated into concrete because their chemical composition, particle size and shape, density, water absorption, and surface characteristics may differ substantially from those of conventional constituents. Therefore, the performance of concrete containing alternative materials should be interpreted in terms of the relationships among mixture composition, internal structure, and the resulting macroscopic properties.

Rice husk ash (RHA) can contain a considerable proportion of amorphous silica when produced under appropriate combustion conditions. The reactive silica can participate in a pozzolanic reaction with calcium hydroxide released during cement hydration, producing additional calcium silicate hydrate (C-S-H) gel. The formation of additional hydration products, together with the filler effect of fine RHA particles, may refine the capillary pore structure and reduce the connectivity of some transport pathways. Such changes may reduce water penetration and ionic transport and consequently increase electrical resistivity under comparable testing conditions. However, replacing cement with RHA also produces a dilution effect by reducing the amount of Portland cement available for hydration. Therefore, the overall effect of RHA on concrete properties depends on the balance between cement dilution, pozzolanic activity, and the physical filler effect. This balance is influenced by the replacement level, fineness, chemical composition, amorphous silica content, burning conditions, and curing regime. Accordingly, RHA incorporation does not necessarily result in simultaneous improvement of all concrete properties; improvements in transport-related indicators may occur even when compressive strength is reduced.

Waste tire rubber powder has substantially different physical and mechanical characteristics from natural mineral aggregates. Its lower density, lower elastic modulus, greater deformability, and hydrophobic surface can modify the interaction between the particles and the surrounding cementitious matrix. The difference in stiffness between rubber and the cement paste, together with relatively weak interfacial bonding, may result in stress-concentration zones and may lead to less efficient stress transfer across the ITZ. Increasing the rubber content can therefore reduce the continuity of the load-bearing mineral skeleton and generally lead to a reduction in compressive strength. At the same time, rubber particles can modify the pore structure and water-transport pathways of concrete. Depending on the rubber content, particle characteristics, and the characteristics of the rubber–cement interface, these changes may increase water absorption or water penetration. The effect of rubber on transport-related properties is therefore not necessarily linear, and an increase in rubber content does not automatically produce a proportional change in electrical resistivity or water penetration. From an environmental perspective, the use of waste rubber powder can contribute to waste-tire valorization and reduce the consumption of natural aggregates; however, its replacement level must be controlled to maintain an acceptable balance between mechanical performance and transport-related properties.

Electrical resistivity is an indirect indicator of the ionic conductivity and connectivity of the pore system in concrete. Electrical current is primarily transported through the ionic solution contained within the pore network; therefore, resistivity is affected by pore connectivity, degree of saturation, pore-solution chemistry, ionic concentration, and total porosity. Refinement of the pore structure and reduction in the connectivity of capillary pores may increase electrical resistivity under comparable moisture and testing conditions. In this respect, the pozzolanic and filler effects of RHA may contribute to increased electrical resistivity. However, electrical resistivity should not be interpreted as a direct or independent measure of overall durability because it is also strongly influenced by moisture condition and pore-solution chemistry. Consequently, its interpretation should be considered together with complementary indicators such as water penetration and water absorption.

The incorporation of an air-entraining admixture introduces an additional mechanism that can modify the internal structure of concrete. Air-entraining admixtures promote the formation of small, relatively stable air voids within the cementitious matrix. The resulting air content can influence workability, density, pore structure, compressive strength, water transport, and electrical resistivity. A controlled amount of entrained air may improve workability and modify the pore system, whereas excessive air content increases the volume fraction of air voids and may reduce the effective load-bearing area of the cementitious matrix, resulting in lower compressive strength. The influence of air entrainment may also depend on the presence and amount of RHA and waste rubber because these materials independently modify the pore structure and interfacial characteristics of concrete. Therefore, the effect of the air-entraining admixture should be evaluated in conjunction with the replacement levels of RHA and waste rubber rather than considered as an isolated factor.

Based on these mechanisms, the theoretical framework of the present study considers RHA, waste rubber powder, and air entrainment as three components that may exert overlapping and competing effects on the mechanical and transport-related performance of concrete. RHA may contribute to pore refinement and improved resistance to water and ionic transport through its pozzolanic and filler effects, while cement dilution may reduce compressive strength at the replacement level considered. Waste rubber powder is expected to reduce compressive strength as its replacement level increases because of its lower stiffness and the relatively weaker rubber–cement interface, while its effects on water transport and electrical resistivity may be non-linear because of changes in pore connectivity and the ITZ. Air entrainment may further reduce density and compressive strength when the air content becomes excessive, while simultaneously modifying water transport and electrical resistivity. Accordingly, the present study evaluates these competing effects by considering compressive strength, water absorption, water penetration under pressure, electrical resistivity, and unit weight. This framework provides a basis for interpreting the experimental results and for identifying mixture compositions that achieve an appropriate balance between mechanical performance, transport-related properties, and the sustainable utilization of agricultural and waste-derived materials.

## 3. Materials and Experimental Studies

### *3.1. Materials*

The coarse aggregates used in this study were crushed with nominal sizes of 12.5–25 mm and 4.75–12.5 mm. The density and water absorption of the coarse aggregate were measured as per ASTM C127 [10]. The density of the aggregate was 2.78 g/cm³, and the water absorption was 0.88%. The particle-size distribution of the mix matched ASTM C33 [11], as illustrated in Figures 1 and 2. The coarse and fine aggregates were taken from an aggregate stockpile on the Imamzadeh Abdullah bypass road, Amol, as illustrated in Figure 3. The fineness modulus of fine aggregate (rounded sand) was 3.06, the density was 2.74 g/cm³, and the water absorption was 1.53% as per ASTM C128 [12]. The maximum particle size of the fine aggregate was 4.75 mm, and its grading was in accordance with ASTM C33 [11], as illustrated in Figure 3. The cement used was Type II Portland cement according to ASTM C150 [13] with a density of 3.15 g/cm³ produced by Neka Cement Factory in Mazandaran Province. Potable water was used for preparing all concrete mixtures and specimens. The commercially available air-entraining admixture (Farsizal Air) produced by Shimi Sakhteman Company, was used as a water-based, chloride–free admixture. It was incorporated at dosages expressed as a percentage by mass of the cementitious materials. The manufacturer's product catalog states that its physical and chemical properties meet the requirements of EN 934-2 [14]. The rice husk ash applied in this study was collected from an industrial area outside Amol. The ash appeared crystalline to gray and had no odor. It contained 88.07% silica and had a loss on ignition of 2.61%. Waste rubber powder was collected from a rubber manufacturer in the same industrial complex in the outskirts of Amol. The manufacturer's product catalog indicated that the particle-size distribution was similar to that of the sand employed in this study, as illustrated in Figure 4.

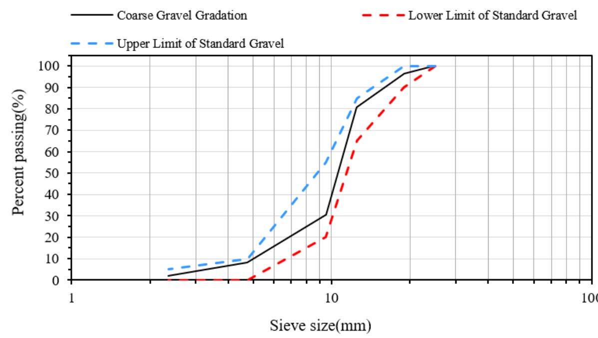


Figure 1. Grading curve of coarse rounded gravel and the permissible limits specified by ASTM C33

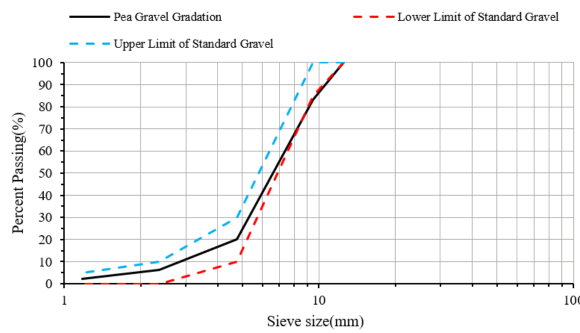


Figure 2. Grading curve of pea gravel and the permissible limits specified by ASTM C33

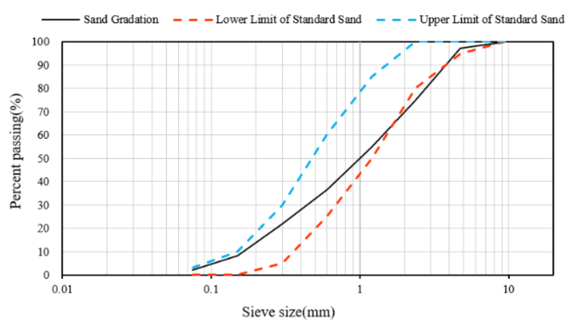


Figure 3. Grading curve of sand and the permissible limits specified by ASTM C33

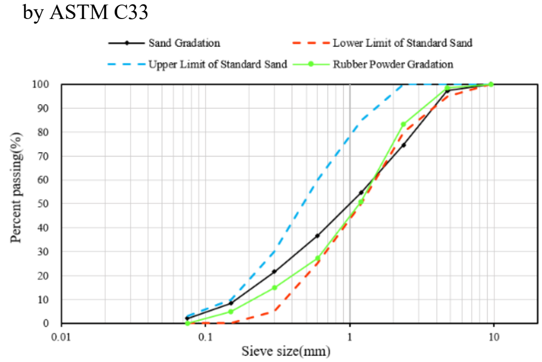


Figure 4. Grading curves of waste rubber powder and sand, with the ASTM C33 permissible limits for sand

### *3.2. Mix Design and Experimental Program*

In the identification of the mixture, the letters C, R, W, and A represent cement, rice husk ash, waste rubber powder, and air-entraining admixture, respectively. The concrete mix preparation and specimen curing are documented in photographs as shown in Figure 5. The proportions of the mixture per cubic meter of concrete were calculated according to the ACI 211.1-91 recommendations and are shown in Table 1 [15]. A total of 11 concrete mixes were prepared, and 209 specimens were cast. Nine specimens with dimensions of 150 × 150 × 150 mm were cast and tested for compressive strength at 7, 28, and 42 days according to EN 12390-3 [16] for each mixture. At 42 days, three cubic samples 150 × 150 × 150 mm were taken from each mixture and tested for water penetration according to EN 12390-8 [17]. Three other cube specimens 150 × 150 × 150 mm were also cast to measure water absorption according to ASTM C642 [18]. Four 100 × 100 × 100 mm cubic specimens were also cast and tested at 42 days to obtain electrical resistivity, as reported by Khanzadi et al. [19]. The samples used to measure the compressive strength were first tested for saturated density of the concrete in accordance with ASTM C642. Table 2 shows the specifications of the laboratory specimens.

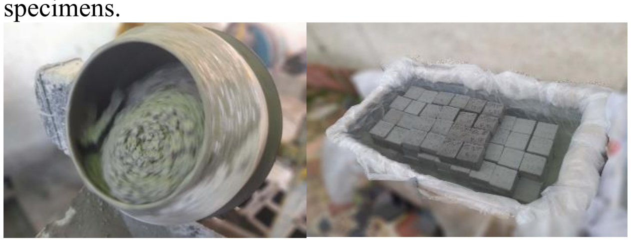

Figure 5. Concrete mix preparation and specimen curing procedures

## 4. Results and Discussion

All tests for the study were carried out in the Structural Engineering Laboratory of the University of North Amol. To assess the impact of rice husk ash and waste rubber powder on the performance of the concrete, mechanical and durability tests were carried out on the formulated mixtures. The experimental results are presented and discussed in terms of compressive strength, electrical resistivity, water penetration, water absorption, and unit weight. The effect of changes in the properties of concrete based on the type and quantity of the materials used in the mixtures was also studied.

### *4.1. Compressive strength*

The effect of the different combinations of RHA and waste rubber powder on the mechanical performance of the concrete was evaluated by compressive strength tests in accordance with EN 12390-3 [16]. The tests were conducted using a fully automatic compression testing machine (CO162) manufactured by Azmoon Saz Mabna, as presented in Figure 6. Standard 150 × 150 × 150 mm cubes were tested at 7, 28, and 42 days. To improve the reliability of the results and reduce the effect of the inherent variability of concrete, three specimens were tested for each mix at each age. The compressive strength of each specimen was calculated, and the average obtained was considered as the strength of the mix at that age. The results for each of the various mixes and ages are presented in Figures 7-10. The results of the development of compressive strength with age and the effect of the RHA and waste rubber replacement level are analyzed below.

Table 1.
Mix proportions of the concrete specimens

| No. | Specimen's Name | Coarse Gravel (kg) | Pea Gravel (kg) | Sand (kg) | Cement (kg) | Rice Husk Ash (kg) | Waste Rubber Powder (kg) | Air-entraining admixture (kg) | Water (kg) | Water-to-Cement Ratio | Total Mixture Mass (kg/m$^3$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | C500 | 425 | 425 | 780 | 500 | 0 | 0 | 0 | 210 | 0.45 | 2340 |
| 2 | C500-R12% | 425 | 425 | 780 | 440 | 60 | 0 | 0 | 210 | 0.45 | 2340 |
| 3 | C500-R12%-W10% | 425 | 425 | 702 | 440 | 60 | 78 | 0 | 210 | 0.45 | 2340 |
| 4 | C500-R12%-W15% | 425 | 425 | 663 | 440 | 60 | 117 | 0 | 210 | 0.45 | 2340 |
| 5 | C500-R12%-W20% | 425 | 425 | 624 | 440 | 60 | 156 | 0 | 210 | 0.45 | 2340 |
| 6 | C500-R12%-W10%-A0.1% | 425 | 425 | 702 | 440 | 60 | 78 | 0.5 | 210 | 0.45 | 2340 |
| 7 | C500-R12%-W10%-A0.2% | 425 | 425 | 702 | 440 | 60 | 78 | 1 | 210 | 0.45 | 2340 |
| 8 | C500-R12%-W15%-A0.1% | 425 | 425 | 663 | 440 | 60 | 117 | 0.5 | 210 | 0.45 | 2340 |
| 9 | C500-R12%-W15%-A0.2% | 425 | 425 | 663 | 440 | 60 | 117 | 1 | 210 | 0.45 | 2340 |
| 10 | C500-R12%-W20%-A0.1% | 425 | 425 | 624 | 440 | 60 | 156 | 0.5 | 210 | 0.45 | 2340 |
| 11 | C500-R12%-W20%-A0.2% | 425 | 425 | 624 | 440 | 60 | 156 | 1 | 210 | 0.45 | 2340 |

Table 2.
Concrete mixture identification and composition

| No. | Mixture | Description |
|---|---|---|
| 1 | C500 | Reference mixture without rice husk ash, waste rubber powder, or air-entraining admixture |
| 2 | C500-R12% | Mixture containing 12% rice husk ash |
| 3 | C500-R12%-W10% | Mixture containing 12% rice husk ash and 10% waste rubber powder |
| 4 | C500-R12%-W15% | Mixture containing 12% rice husk ash and 15% waste rubber powder |
| 5 | C500-R12%-W20% | Mixture containing 12% rice husk ash and 20% waste rubber powder |
| 6 | C500-R12%-W10%-A0.1% | Mixture containing 12% rice husk ash, 10% waste rubber powder, and 0.1% air-entraining admixture |
| 7 | C500-R12%-W10%-A0.2% | Mixture containing 12% rice husk ash, 10% waste rubber powder, and 0.2% air-entraining admixture |
| 8 | C500-R12%-W15%-A0.1% | Mixture containing 12% rice husk ash, 15% waste rubber powder, and 0.1% air-entraining admixture |
| 9 | C500-R12%-W15%-A0.2% | Mixture containing 12% rice husk ash, 15% waste rubber powder, and 0.2% air-entraining admixture |
| 10 | C500-R12%-W20%-A0.1% | Mixture containing 12% rice husk ash, 20% waste rubber powder, and 0.1% air-entraining admixture |
| 11 | C500-R12%-W20%-A0.2% | Mixture containing 12% rice husk ash, 20% waste rubber powder, and 0.2% air-entraining admixture |


Figure 6. The fully automatic compression testing machine

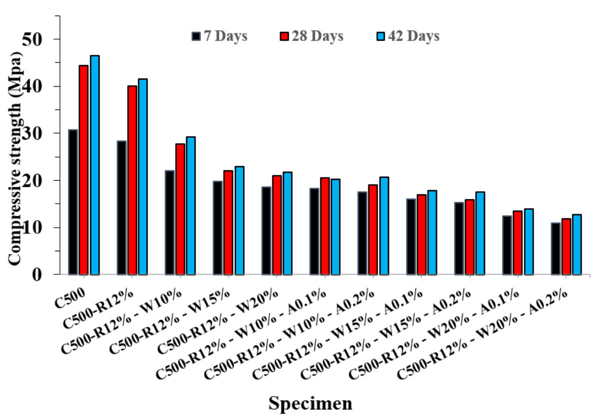


Figure 7: Comparison of compressive strength of the specimens at 7, 28 and 42 days

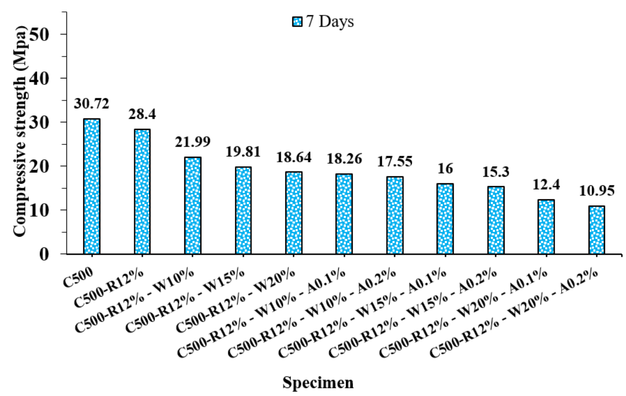


Figure 8. Comparison of compressive strength of the specimens at 7 days

The compressive strength test at 7, 28, and 42 days revealed that the partial replacement of cement with RHA, the use of waste rubber powder, and the addition of an air-entraining agent substantially affected on the strength behavior of the mixes. The control mix (C500) was 30.72, 44.4, and 46.5 MPa at 7, 28, and 42 days, respectively, and was used as the reference for the other mixes. The gradual development of the cement paste structure at later ages is reflected by the increase in strength from 30.72 MPa at 7 days to 44.4 MPa at 28 days and 46.5 MPa at 42 days. The strength of the control mix increased by 28 days, and the increase in strength between 28 and 42 days was only about 4.6%. The compressive strength at all ages decreased with the addition of 12% RHA compared to the control. C500-R12% had an increase in strength from 28.4 MPa at 7 days to 40 MPa at 28 days and 41.6 MPa at 42 days, representing decreases of 7.5%, 9.9%, and 10.5% at the same ages compared to the control. The negative impact of substituting a portion of the cement on the early and final compressive strength was greater than the strengthening effect of the pozzolanic reaction for the conditions of this study and a 12% replacement rate. Despite this, the strength of this mix at 42 days (41.6MPa) was 46.5% higher than at 7 days (28.4MPa), indicating that secondary reactions and the development of the matrix structure continued at later ages. The reducing effect of the mixture of RHA and waste rubber powder was much more significant. In the mix with 12% RHA and 10% rubber powder, the compressive strength at 7, 28, and 42 days was 22, 27.8, and 29.3 MPa, respectively, 28.4%, 37.4%, and 37% below the control. This reduction is due to the different mechanical properties of rubber and the cementitious matrix, as well as the relatively weak bond between the rubber particles and the cement paste in the transition zone. The modulus of elasticity and stiffness of rubber particles are much lower than those of the mineral component of the matrix, and the presence of rubber particles can disrupt the load-bearing cementitious skeleton and create stress concentration around the rubber particles. Furthermore, the relatively hydrophobic surface of the rubber may not allow for a good bond with the cement paste and thus encourage the development of weaker zones around the rubber particles. The effect of the rubber content is even more pronounced at later ages when the amount of rubber powder in the mixes is increased to 10%, 15% and 20% of the sand by mass. At 28 days, increasing the waste rubber powder content from 10% to 15% reduced the compressive strength from 27.8 to 22.1 MPa, while a further increase in the rubber content to 20% reduced the strength to 21.0 MPa. Relative to the control, the 28-day strength loss thus grew from 37.4% for W10% to 50.2% and 52.7% for W15% and W20%. The same trend was seen at 42 days, where the losses for W10%, W15%, and W20% were 36.9%, 50.6%, and 53.1%, respectively. The results indicate that the higher the rubber content, the lower the absolute strength and the greater the performance difference between the rubber mixes and the control. The larger the volume of rubber particles, the more they will interfere with the continuity of the cementitious phase, and the more they will increase the volume of weak transition zones and decrease the effective paths for stress transfer at the microstructural level. The compressive strength of mixes with R12% and W decreased even more when an air-entraining agent was added. For the mix with 10% rubber, adding 0.1% air-entraining agent reduced the strength at 7, 28, and 42 days to 18.26, 20.5, and 20.2 MPa, respectively, 40.5%, 53.8%, and 56.5% below the control. Raising the dosage from 0.1% to 0.2% gave 17.55, 19 and 20.7 MPa, reductions of 42.8%, 57.2% and 55.5% relative to C500. This behavior indicates that, under the present test conditions, creating more air bubbles in the matrix had a mainly adverse effect on the compressive load-bearing capacity. Air voids decrease the effective area for stress transfer in the matrix, and may also increase the concentration of stresses around the pores, making it easier for compressive cracks to start. The effect of the rubber and air-entraining agent may then be additive in reducing the load-bearing properties of the mix. The greatest strength loss was seen in the mixes with 20% rubber and air-entraining agent. In C500-R12%-W20%-A0.1%, the compressive strength at 7, 28, and 42 days was 12.4, 13.5, and 14 MPa, 59.6%, 69.6%, and 69.9% below the control. Raising the air-entraining agent to 0.2% reduced the strength to 10.95, 11.9, and 12.8 MPa, with losses of 64.3%, 73.2%, and 72.4% relative to C500. The modified mixes had the highest compressive strength of C500-R12%-W10% with a value of 29.3 MPa at 42 days, which is approximately 36.9% lower than the control. C500-R12%-W20%-A0.2%, with 12.8 MPa at 42 days, had the lowest strength, about 72.4% below C500.

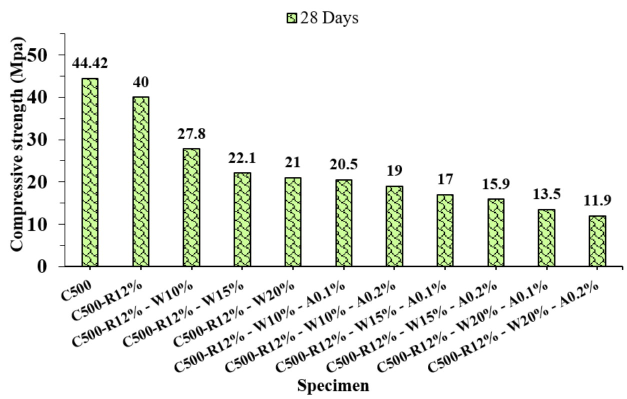


Figure 9. Comparison of compressive strength of the specimens at 28 days

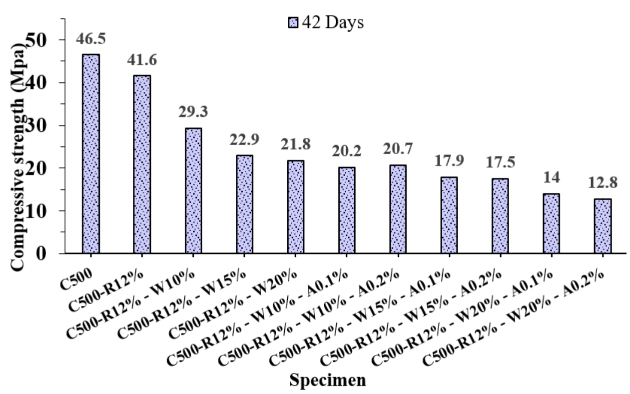


Figure 10. Comparison of compressive strength of the specimens at 42 days

### *4.2. Volumetric electrical resistivity*

Electrical resistivity of concrete was measured at 42 days to characterize the electrical properties of the concrete and to use it as an index of concrete durability and resistance to penetration of aggressive ions. ASTM has published a standard for electrical conductivity of concrete, C1760-12, but no standard procedure exists in BS, ASTM, or other recognized standards for the measurement of the electrical resistivity of hardened concrete, so particular equipment and methods have been used for this purpose [19]. In this study, the two-point method was used to determine the bulk electrical resistivity. Four 100 × 100 × 100 mm cubes from each mix were tested at 42 days. All specimens were stored under the same saturated conditions in normal water prior to testing. After removal from the water, two opposite faces of each specimen, in the saturated surface-dry condition, were coated with a thin layer of cement paste. Copper plates were then placed on the prepared faces as electrodes to provide good electrical contact between the measuring instrument and the specimen. The arrangement is displayed in Figure 11. These were then placed under an alternating current of fixed frequency, and the electrical resistance was measured and recorded for 1 minute. The resistance of the specimens was measured for each mix, and the electrical resistivity of the concrete was determined using Equation (1). The resistivity results for the different mixes are shown in Figure 12.

$$\rho = \frac{R.A}{L} \tag{1}$$

where ρ represents the electrical resistivity (Ω.m), R is electrical resistance (Ω), A is the cross-sectional area of the specimen (m2) and L is the length of the specimen (m).

The criterion for interpretation of the electrical resistivity of concrete in terms of the probability of reinforcement corrosion is provided in Table 3.

Table 3.
Criterion used to interpret the electrical resistivity of concrete in terms of the probability of reinforcement corrosion [20]

| **Electrical resistivity of concrete** | **Probability of reinforcement corrosion** |
|---|---|
| Above 120 Ω.m | Not probable |
| 50 - 120 Ω.m | Probable |
| Below 50 Ω.m | Imminent |

The electrical resistivity results at 42 days revealed that the partial replacement of cement with RHA, addition of waste rubber powder, and air-entraining agent had a significant influence on the transport properties of the concrete and consequently on the possibility of reinforcement corrosion. The resistivity of the control mix, C500, was 98.3 Ω·m. Based on the classification adopted in this study, corrosion is probable if the resistivity is in the range 50 to 120 Ω·m, corrosion is Not probable if the resistivity is above 120 Ω·m, and corrosion is Imminent if the resistivity is below 50 Ω·m. The control mix, 98.3 Ω·m, is thus in the range where corrosion is probable and, on this basis, cannot be considered totally not probable. The resistivity was increased by about 21.6% with the addition of 12% RHA from 98.3 Ω·m to 119.5 Ω·m. This value is still just below the threshold of 120 Ω·m, but by the criterion used, it is still within the range where corrosion is probable; the significant increase in resistivity indicates that RHA enhanced the transport properties of the cementitious matrix. An increase was seen with the mix that contains 10% rubber powder. C500-R12%-W10% had a resistivity of 143.9 Ω·m, 46.4% higher than the control. This is greater than the 120 Ω·m limit and, using the criterion, the specimen is in a range that is not conducive to reinforcement corrosion. Increasing the rubber content from 10% to 15% lowered the resistivity to 88.8 Ω·m, 9.6% less than the control and approximately 38.3% less than the W10% mix. The resistivity of W20% was 96.4 Ω·m, approximately 1.9% lower than that of the control, and this mix also had a resistivity in the range where corrosion is probable. The present data thus indicate that the resistivity changes with the rubber content in a non-linear manner and that the best rubber content for electrical properties is not necessarily the highest rubber content. The resistivity of C500-R12%-W10%-A0.1% was 85.5 Ω·m, which is approximately 13% below the control, and within the range where corrosion is likely to occur. The air-entraining agent was raised from 0.1% to 0.2% to increase resistivity to 114.3 Ω·m, which is 16.3% higher than the control, but still does not meet the resistivity requirement of 120 Ω·m and remains in the corrosion-probable class. The highest resistivity of all the mixes was for C500-R12%-W15%-A0.1% at 181.7 Ω·m, an increase of 84.8% from the control. This is much higher than the 120 Ω·m limit, and according to the criterion, reinforcement corrosion is not likely. The mixes containing 20% rubber also exhibited different properties. The resistivity of C500-R12%-W20%-A0.1% was 130.7 Ω·m, 33% higher than the control, and in the range where corrosion is Not probable, exceeding the limit of 120 Ω·m.

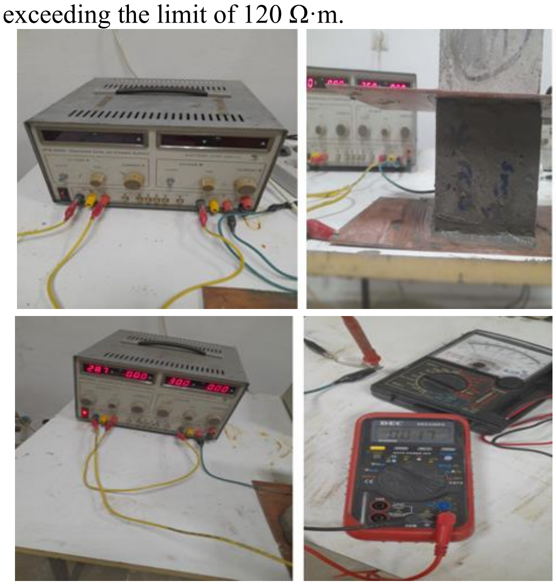

Figure 11. Specimen configuration for electrical resistivity measurement

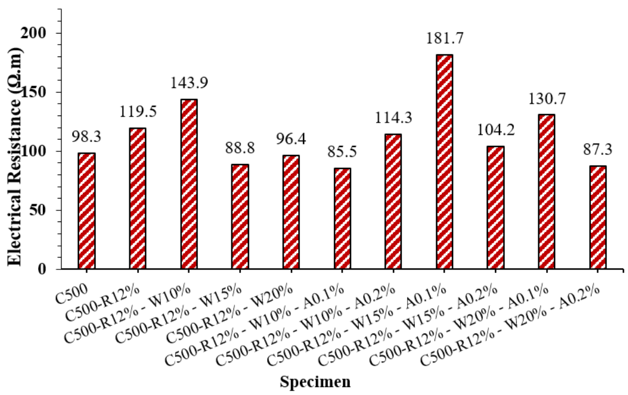


Figure 12. Comparison of the electrical resistivity of concrete specimens at 42 days

### *4.3. Permeability*

The water penetration depth under pressure was measured as per EN 12390-8 [17] by using a permeability apparatus (CO952-950) manufactured by the company Azmoon Saz Mabna to evaluate the resistance of the concrete to water penetration under pressure and to investigate the effect of different mixes of RHA and waste rubber powder on permeability. The placement of the specimen in the apparatus and the test set-up are shown in Figure 13. Three specimens of each mix were used at 150 × 150 × 150 mm, and tested at 42 days. The prepared specimens were then loaded into the apparatus and subjected to water pressure of 500 kPa for 72 hours. The specimens were removed at the end of the pressure period and split into two halves, and the depth of the water penetration front on the fracture surface of each specimen was measured with a graduated ruler and calipers. The mean value of the three specimens was used as the representative value for each mix. The smaller penetration depth means the lower ability of water to penetrate the concrete structure and therefore the higher resistance to water penetration. The results for the different mixes are shown in Figure 14.

The water penetration test conducted at 42 days in accordance with EN 12390-8 has revealed that the use of RHA, waste rubber powder, and an air-entraining agent in the concrete mix has substantially affected water penetration into the concrete. Unlike compressive strength and electrical resistivity, the measured value for water penetration resistance in EN 12390-8 is the depth of water penetration under pressure. The penetration depth of the control mix, C500, was 40 mm and was used as a reference. The replacement of 12% cement with RHA reduced the penetration depth from 40 mm to 24.7 mm, which is a reduction of 38.2% compared to C500. The significant improvement, however, is the resistance of the concrete to water penetration under pressure, even though a loss of compressive strength was observed with the 12% RHA. The penetration depth increased from 24.7 mm for the R12% mixture to 32.3 mm after incorporating 10% waste rubber powder. Nevertheless, the penetration depth remained 19.25% lower than that of the control mixture, indicating that the addition of rubber partially offset the reduction in water penetration achieved by RHA; 10% rubber offset part of this improvement. The penetration depth was appreciably increased by raising the rubber content from 10% to 15%; for C500-R12%-W15%, it was 36.5 mm, which is 8.75% lower than the control. The penetration depth increased further to 39.9 mm at 20% rubber replacement, which was higher than the value obtained for the 15% rubber mixture (36.5 mm) and was close to that of the control mixture (40 mm) and indicates that the water penetration with increasing rubber content is not linear, as the W20% had a lower compressive strength but a similar penetration depth to the control. In some of the rubber mixes, water penetration increased with the addition of 10% rubber, but in the present case it decreased. The penetration depth was reduced by approximately 5.0%, from 32.3 mm in W10% to 30.7 mm with the addition of 0.1% air-entraining admixture, which is approximately 5% less than the penetration depth of the R12%-W10% mix without air-entraining agent. A higher dose of 0.2% resulted in a penetration depth of 32.2 mm, which was approximately 19.5% less than C500. With 10% rubber, however, the air-entraining agent used in this range had a significant effect in reducing the water penetration. The lower penetration depth of the mixes with air-entrained can be explained by the change in the structure and connectivity of the pore network. However, it is important to note that the presence of air bubbles is not always correlated with reduced permeability, but rather depends on the distribution, size, spacing, and connectivity of the air bubbles. In the mixes with 20% rubber, the air-entraining agent acted differently: C500-R12%-W20%-A0.1% had the largest penetration depth of all the mixes, 48.8 mm, 22% above the control. Thus, under the existing conditions, a combination of 20% rubber and an air-entraining agent provided the least water penetration resistance.


Figure 13. Specimen configuration for concrete permeability test

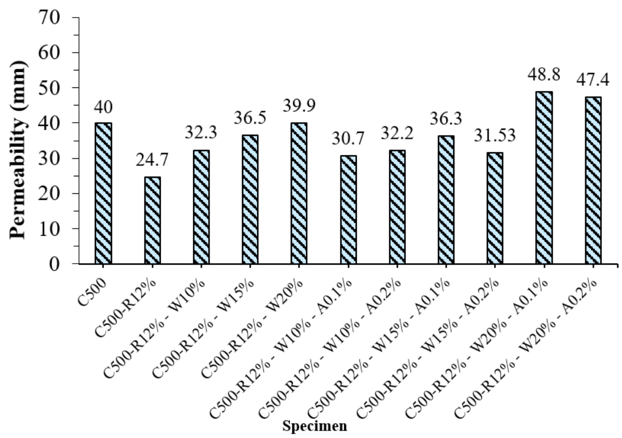


Figure 14. Comparison of the permeability of concrete specimens at 42 days

### 4.4. Water absorption

Water absorption tests were conducted following ASTM C642 [18] to evaluate the water absorption and to investigate the effect of RHA and waste rubber powder on the porosity and permeability-related properties of the concrete. Each mix was made into three 150 x 150 x 150 mm cubes, which were tested at 42 days, and the average of the three was used as the water absorption of that mix. The specimens were cured in a water tank at a controlled temperature of 23 ± 2 °C and then taken out; the surface moisture was wiped off, and the specimens were ready for dry mass determination. They were then put into an oven at 100 to 110 °C for 24 hours, removed, cooled to room temperature, and weighed; this weight was noted as the dry mass. The oven and the weighing of the specimens are shown in Figure 15. The dried specimens were then placed in a water tank at approximately 21 °C and left to become water saturated. They were removed from the water after at least 48 hours; the excess surface moisture was gently removed with a dry towel, and the specimens were weighed immediately, and this mass was recorded as the saturated surface-dry mass. For each specimen, water absorption was determined as the difference between the mass of the saturated surface-dry specimen and the mass of the dry specimen, expressed as a percentage of the mass of the dry specimen. Water absorption was used as an index of the pore structure of the concrete and of the access of water to the pore network. The results of the mixes studied after 42 days are presented in Figure 16 and compared with the values presented in Table 4, which provides the relationship between concrete quality and water absorption as recommended by CEB-FIP [21].

The water absorption results after 42 days indicate significant differences in the water absorption behavior of the mixes. The control mix C500 was used as a reference. Replacing 12% of the cement with RHA increased the water absorption of the concrete from 2.47% to 3.94%, representing a 59.5% increase compared with the control. This indicates that the pozzolanic reaction products that can be formed and the microstructure refinement effect of RHA at later ages, due to its pozzolanic properties and the presence of reactive silica, were not significant in this mix at 42 days; thus, the increase in water absorption prevailed. In R12%-W15%, the water absorption was 3.66%, 48.2% above the control. In contrast to W10, the water absorption significantly increased with the addition of 10% to 15% rubber. This means that the influence of rubber powder on the pore structure is not always linear: the greater the amount of rubber powder, the greater the possibility of the appearance of voids, discontinuities in the transition zone between the paste and rubber, and the appearance of additional permeable paths.

The water absorption was 4.67% at 20% rubber, which was 89% higher than the control. The water absorption increased when adding the air-entraining agent to the R12%-W10% mix, compared to the very low value of the mix without an air-entraining agent. The water absorption of R12%-W15%-A0.1% was 5.26%, which was 113% more than the control and the highest among all the samples. The 15% rubber and 0.1% air-entraining agent thus resulted in the worst performance in water absorption under the present test conditions.

Table 4.
The relationship between water absorption and concrete quality [21]

| Water absorption percentage | Concrete quality |
|---|---|
| Above 5% | Poor |
| 3 – 5% | Mediocre |
| Below 3% | Good |


Figure 15. Oven and specimen weighing

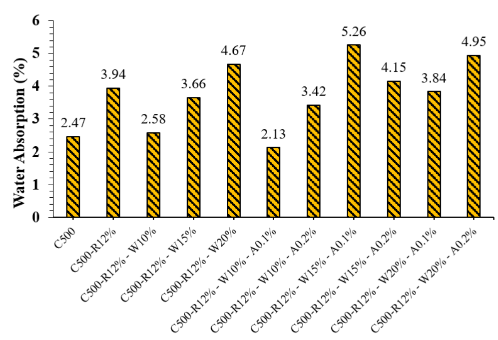


Figure 16. Comparison of the water absorption percentage of specimens at 42 days

### *4.5. Unit weight*

The density of the specimens was measured according to ASTM C642 [18] to investigate the influence of using RHA and waste rubber powder as cement and sand replacements, respectively, on the density of the concrete and to assess the changes in unit weight. The test was conducted on cubes at 7, 28, and 42 days. Three samples were tested at each age for each mix, and the mean density was used as the representative density. After curing, the specimens were removed from the water tank and prepared for mass determination in the required moisture condition following the test method. The mass was determined using a suitable balance of appropriate accuracy, and the density was determined by dividing the mass by the volume. The nominal dimensions of the specimens were fixed, and the volume of each specimen was determined by the geometry. The density of concrete may be influenced by the type and quantity of substitute material, the difference in the particle density of the constituents, and the changes brought about in the internal structure. RHA and waste rubber powder, in particular, whose densities are significantly different from those of cement and natural aggregate, can alter the unit weight of the concrete. The density of the concrete at various ages can thus be used to gain information on the unit weight of the mixes and to evaluate the influence of the substitute materials on the physical changes in concrete during curing. The density results at 7, 28 and 42 days are shown in Figures 17 to 20, and their trends are analyzed and compared below.

At 7 days, the unit weight of the control concrete was measured as 2482 kg/m³. Replacing 12% of the cement with rice husk ash reduced the unit weight to 2361 kg/m³, corresponding to a 4.9% reduction compared with the control concrete. This reduction can be attributed to the lower specific gravity of rice husk ash compared with cement, as well as the more porous nature of the ash particles. With the addition of 10% waste rubber powder to the rice husk ash-containing mixture, the unit weight reached 2110 kg/m³, representing a 15.0% reduction compared with the control concrete. Increasing the rubber content to 15% and 20% resulted in unit weights of 2159 and 2208 kg/m³, respectively, corresponding to reductions of 13.0% and 11.0% compared with the control concrete. With the air-entraining agent, the unit weight of W10-A0.1 was 2211 kg/m³, 10.9% below the control, and at 0.2% it fell to 2120 kg/m³, a reduction of 14.6%. This decrease is in line with the action of an air-entraining agent, which is to increase the void volume and thus reduce the unit weight. The unit weight of the control concrete was 2462 kg/m³ at 28 days. The replacement of 12% RHA in cement slightly increased the unit weight to 2479 kg/m³, which is 0.7% higher than the control, but not of much practical significance as compared to 7 days. This change could be due to hydration and pozzolanic reactions within the concrete at later ages. The unit weight of the rubber addition of 10% was reduced to 2162 kg/m³, which is 12.2% below the control. W15 and W20 gave 2176 and 1963 kg/m³, reductions of 11.6% and 20.3%. The greatest decrease for the mixes at 28 days was for W20%, which did not contain an air-entraining agent. The unit weight of the concrete W20-A0.2 was 1973 kg/m³ at 42 days, which was 20% lower than the unit weight of the control concrete.

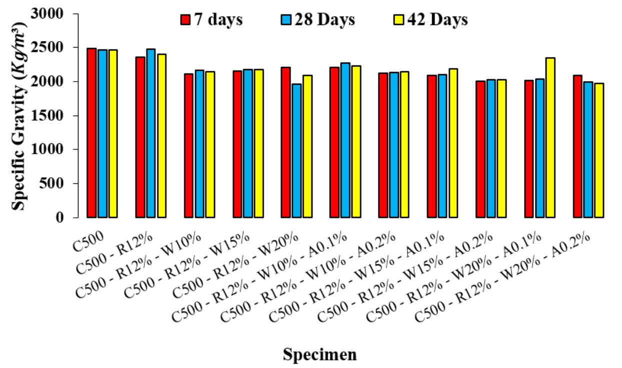


Figure 17. Comparison of the unit weight of the specimens at 7, 28 and 42 days

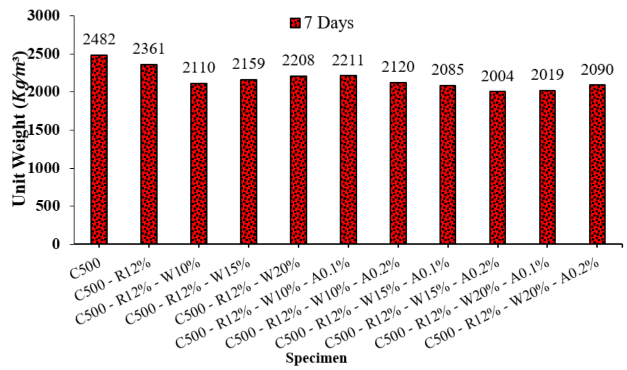


Figure 18. Comparison of the unit weight of the specimens at 7 days

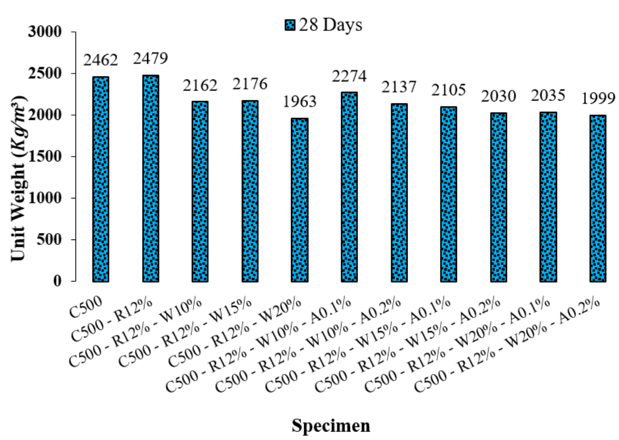


Figure 19. Comparison of the unit weight of the specimens at 28 days

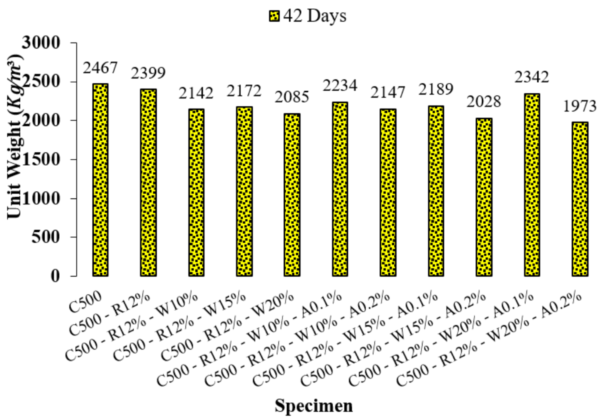

Figure 20. Comparison of the unit weight of the specimens at 42 days

## 5. Conclusions

The experimental results demonstrate that rice husk ash (RHA), waste rubber powder (WRP), and an air-entraining admixture produce different and sometimes competing effects on the mechanical and transport-related properties of concrete. Replacing 12% of cement with RHA reduced the 42-day compressive strength from 46.5 to 41.6 MPa, while increasing electrical resistivity from 98.3 to 119.5 Ω·m and reducing water penetration depth from 40 to 24.7 mm. The incorporation of WRP generally reduced compressive strength, with the highest 42-day strength among the rubber-containing mixtures being 29.3 MPa at a 10% replacement level. Its effects on electrical resistivity and water penetration were non-linear. The highest electrical resistivity, 181.7 Ω·m, was obtained for the mixture containing 12% RHA, 15% WRP, and 0.1% air-entraining admixture. The air-entraining admixture generally reduced compressive strength relative to the corresponding rubber-containing mixtures without air entrainment, although the effect of increasing its dosage from 0.1% to 0.2% was not strictly monotonic.

Overall, the results indicate that the combined use of RHA and WRP can modify the mechanical and transport-related performance of concrete, but improvement in one property does not necessarily correspond to improvement in the others. Electrical resistivity should therefore be interpreted together with compressive strength, water absorption, and water penetration rather than as an independent measure of overall durability. Within the investigated ranges, RHA and WRP show potential for use in more sustainable concrete applications, provided that their proportions are selected according to the required balance between mechanical and transport-related performance. The findings are limited to the specific materials, replacement levels, and admixture dosages investigated and should not be directly extrapolated to other mixture proportions.

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