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VALORISATION OF THE EFFECT OF WASTE ALUMINUM SAWDUST ON CONCRETE: DURABILITY CHARACTERISTICS AND ENVIRONMENTAL IMPACTS

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Abstract: The aim of this study is to examine the effect of replacing waste aluminum sawdust (AS) with fine aggregate on the strength and durability properties of concrete. For this, concrete mixtures with a cement dosage of 400 kg/m^3, water/cement (W/C) ratio of 0.40-0.50-0.60 were prepared. Aluminum sawdust obtained from Elazığ industrial site was added to the concrete mixtures by replacing 0%, 0.5% and 1% fine aggregate by volume. After curing in the curing pool for 28 days, the produced concrete samples were placed in the carbonation tank and exposed to the accelerated carbonation test in three different time periods as the 1st, 3rd and 7th days. Tests of compressive strength, splitting tensile strength, ultrasound transmission velocity, porosity and carbonation depth were performed on concrete samples before and after carbonation. The samples that were exposed to carbonation were compared with the samples that did not undergo carbonation. In addition, the microstructure of AS concrete was investigated using scanning electron microscopic images (SEM). In the microscopic images, larger cracks, openings and interfacial voids were observed in the concrete matrix with the addition of AS. However, due to the formation of ettringite in these gaps and cracks after carbonation, the cavities became smaller. As a result of the experiments, it was observed that the optimum W/C ratio was 40% and the AS amount was 0.5% in the use of AS in concrete. In addition, it was found that the carbonation effect improves the compressive and splitting tensile strength and increases the ultrasound transmission rate. Finally, life cycle assessment (LCA) was conducted to evaluate the environmental impacts of the prepared concrete samples. Considering the large amount of natural aggregate consumption, it is thought that the use of waste materials in concrete will provide environmental and economic benefits.

Keywords: Aluminium sawdust, Carbonation, Hardened properties, Microscopic image, Life cycle assessment

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1. Introduction

With the continuity of continuity of the construction sector and the emergence of new needs in the field of construction, there is a great increase in concrete production (Ramachandran and Beaudoin, 2001). This rising increase in the construction sector also increases the production of concrete and increases the use of aggregate, one of the main components of concrete. This leads to rapid depletion of natural resources (Osei and Jackson, 2016). For the protection of the ecosystem and sustainable development, it becomes necessary to reduce the use and accumulation of waste products. Many studies on the use of waste materials silica fume, fly ash, blast furnace slag, waste foundry sand, wood ash, etc. as partial substitutes for natural materials in concrete production have facilitated to reduction of dependence on natural materials (Siddique et al., 2020).

The expansion of construction has an important role in the increase in environmental problems. Buildings produce harmful emissions and wastes by consuming natural resources and energy during their lifetime. As a result, they create environmental pollution (Golewski, 2021). It is estimated that around 11 billion tons of aggregate is consumed every year worldwide. Approximately 8 billion tons of this aggregate amount is used in concrete production (Golewski, 2021). This situation poses a great threat to the environment. In addition, the transportation process of these aggregates also brings great cost (Babu et al., 2015). Therefore, the use of industrial by-products in concrete production has become a necessity in order to protect the environment and contribute to the economy (Cheng, et al., 2013).

The use of recyclable materials in buildings requires many processes such as disassembling these materials for recycling, collecting, grouping and obtaining a new product. However, it will provide significant environmental benefits in terms of raw material savings, resource efficiency, energy efficiency and reduction of environmental pollution (Miličević et al., 2011; Martínez-Lage et al., 2020). For this purpose, scientific researches continue to be carried out on the recycling of industrial wastes that pose an environmental threat and their use in concrete, in the construction sector as well as in many other sectors. In these studies, materials such as metal powder and sawdust, steel and wood chips, aluminum powder and sawdust are used in the production of concrete (Alwaeli and Nadziakiewicz, 2012; Zhong et al., 2018). Among these materials, aluminum sawdust is one of the newest waste materials (Öztürk, 2020).

Aluminum sawdust (AS) is a waste material produced by the industrial industry. In the aluminum industry, which is one of the most advanced recycling industries today, approximately 50% of the aluminum used in the world is recovered. Aluminum production from scrap is 95% more efficient than primary aluminum production (Binici et al., 2013). The application of AS can not only reduces environmental damage but also can save concrete materials. Substituting cement in concrete contributes to more economical and environmentally friendly concrete production by reducing the amount of cement usage. It also has many advantages over traditional concrete, such as low bulk density, better heat preservation and less pollution to our environment (Cheng et al., 2013).

Considering the type and severity of external effects that they will be exposed to during their service life while the structures are being designed ensures that the structures can maintain their functionality throughout their lifetime. A concrete designed according to the environmental conditions, produced in high quality, well placed and cared for can fulfill its duty for many years without any repair. However, the performance of concrete may decrease in the face of some internal and external factors. A durable concrete; It is concrete that resists these effects (Demir et al., 2022). Exposed and unprotected reinforced concrete structures cause corrosion damage. In Türkiye; it was observed that corrosion damage occurred in many of the structures damaged in the earthquake. There is also the danger of corrosion in our existing structures. The most important factor causing corrosion is carbonation. Carbonation also causes deterioration of the durability of the structures (Balapour et al., 2018; Flores et al., 2015).

In previous literature studies, the mechanical properties of wastes such as wood shavings, glass dust, and marble powder on concrete were generally investigated. However, there are hardly any studies on the use of AS in concrete production. The aim of this study is to examine the effect of the use of waste aluminum sawdust (AS) by replacing it with fine aggregate on the strength and durability properties of concrete, to contribute to the improvement of concrete, to prevent environmental pollution by evaluating waste materials, and to determine the replacement rate of AS with fine aggregate and to contribute to the literature to present relevant data. After literature research, many trial mixtures were poured to determine material mixing ratios. After these trial mixtures, reference mixtures were determined. For this, concrete mixtures with a cement dosage of 400 kg/m^3, W/C ratio of 0.40, 0.50% and 0.60% were prepared. Aluminum sawdust obtained from Elazığ industrial site was added to the concrete mixtures by replacing 0%, 0.5% and 1% fine aggregate by volume. After curing in the curing pool for 28 days, the produced concrete samples were placed in the carbonation tank and exposed to the accelerated carbonation test in three different time periods as the 1st, 3rd and 7th days. Tests of compressive strength, splitting tensile strength, ultrasound transmission velocity, and porosity and carbonation depth were performed on concrete samples before and after carbonation. The samples that were exposed to carbonation were compared with the samples that did not undergo carbonation. In addition, the microstructure of AS concrete was investigated using scanning electron microscopic images. In the microscopic images, larger cracks, openings and interfacial voids were observed in the concrete matrix with the addition of AS. However, due to the formation of ettringite in these gaps and cracks after carbonation, the cavities became smaller. As a result of the experiments and cost comparison, it was found that the optimum W/C ratio was 40% and the amount of AS was 0.5%. In addition, it was found that the carbonation effect improves the compressive and splitting tensile strength, and increases the ultrasound transmission rate.

2. Constituent Materials and Mix Details

2.1. Materials

In this study, CEM I 42.5 R Portland cement obtained from Elazığ Çimentaş cement factory was used (TS EN 197-1, 2012). In the experiments, river aggregate with the largest grain diameter (Dmax) of 8 mm, obtained from Palu District of Elazığ Province, was used. Aggregate; It was used in three classes: 0-2 mm, 2-4 mm and 4-8 mm. Aluminum Sawdust (AS) was used as waste material. AS was supplied from Elazığ industrial zone. The chemical properties of these materials are given in Table 1.

Aluminum is one of the newest members of the metal world. Aluminum, which is in the light metal class, is widely used due to its advantages in technical properties (Zhang et al., 2023). When various alloys are added, their mechanical properties reach levels comparable to steel. It is widely used in various industrial fields such as medicine, food, aerospace, automotive and construction (Geçkinli, 2002). The appearance of the AS used in the study is shown in Figure 1.

2.2. Mix Design and Sample Preparation

In this study, 9 concrete mixtures with cement dosage of 400 kg/m^3, W/C ratio of 0.40-0.50-0.60, respectively, were prepared in order to examine the variation range of strength properties of AS-reinforced concretes at fixed cement dosage at different ratios. In these mixtures, 0.5% and 1.0% AS was used by replacing the fine aggregate by volume. 3 different concrete series were prepared for the control series without AS (free carbonation) and 6 different concrete series were prepared at the rates of 0.5% and 1.0% for the series with AS. Details of mixing ratios are summarized in Table 2.

Table 1. Chemical properties of materials used in the study

Chemical properties	Cement (C)	Chemical properties	Aluminium Sawdust (AS)
CaO	63.33	Al	89.96
SiO_2	19.07	Zn	4.97
Fe_2O_3	3.72	Mg	2.11
Al_2O_3	4.82	Cu	0.26
SiO_3	2.83	Mn	0.25
Na_2O	0.39	Fe	0.24
K_2O	0.65	Si	0.15
MgO	1.10	Cr	0.025
Cl	0.009	Ti	0.012
Insoluble residue	0.20	Pb	0.005
Loss of ignition	2.70	Sn	0.003

Figure 1. Aluminium sawdust sample used in the study.

Table 2. Proportions of the concrete mixtures (kg/m^3)

Mixture Code	Cement	Water	AS	Fine aggregate (0-2) mm	Fine aggregate (2-4) mm	Coarse aggregate (4-8) mm
0.4AS0	400	186.59	0.00	562	544	659
0.4AS5	400	186.59	3.11	559	544	659
0.4AS10	400	186.59	6.21	556	544	659
0.5AS0	400	225.02	0.00	528	512	620
0.5AS5	400	225.02	2.92	526	512	620
0.5AS10	400	225.02	5.85	523	512	620
0.6AS0	400	263.44	0.00	495	480	581
0.6AS5	400	263.44	2.74	493	480	581
0.6AS10	400	263.44	5.48	490	480	581

2.3. Production of Samples and Testing Program

Within the scope of the study, 9 series with and without AS were prepared to investigate the effect of AS on pre- and post-carbonation compressive strength, splitting tensile strength, ultrasound transmission rate, porosity test and carbonation depth measurement. For the implementation of all tests, a total of 216 concrete samples, 24 in each concrete series, were produced. Flow chart of the study is shown in Figure 2.

2.4. Experimental Methods and Procedures

2.4.1. Compressive strength

Compressive strength test of concrete samples was determined according to TS EN 12390-3 standard (TS EN 12390-3, 2019). The 100x100x100 mm specimens were placed in the compression testing machine and were loaded at 3 kN/sec. The average compressive strength of three cube specimens of each concrete mixture was termed as the compressive strength of that concrete mixture.

2.4.2. Split Tensile Strength

Splitting tensile strength test is determined according to TS EN 12390-6 standard (TS EN 12390-6, 2010). The cube specimens (100x100x100 mm) were placed in the compression testing machine and were loaded at 0.47 kN/sec. 100 mm long iron pieces were placed on the upper and lower parts of the samples in order to prevent the samples from disintegrating and fragmenting and to ensure fracture in a uniform section.

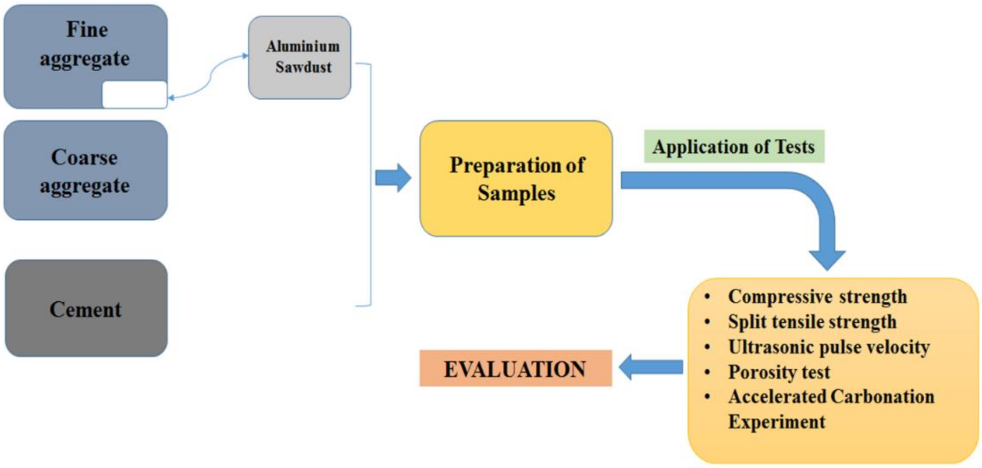
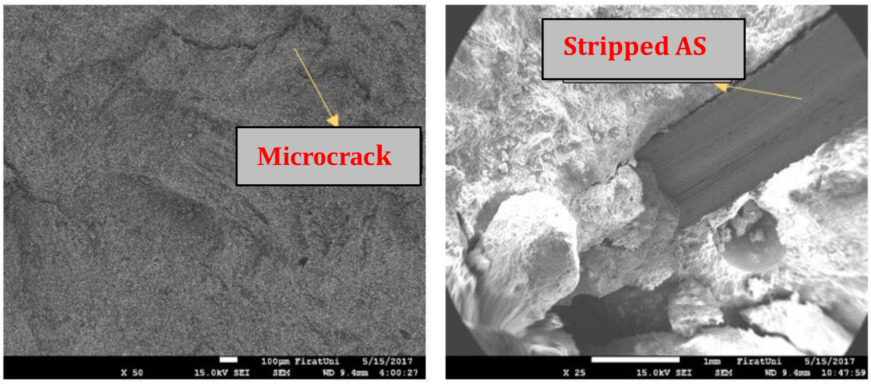


Figure 2. Flow chart of the study.



(a) (b)

Figure 3. SEM image of the sample (a) without AS (b) with AS.

The average compressive strength of three cube specimens of each concrete mixture was termed as the compressive strength of that concrete mixture. Splitting tensile strength of concrete specimens was calculated as given in the Equation 1.

$$f_{ct}=\frac{2P}{\pi DL} \tag{1}$$

where;

f_{ct} : Split-tensile strength of concrete in MPa
P : Maximum load N
D : Diameter of the cube-specimen in 'mm'
L : Length of the cube-specimen in 'mm'.

2.4.3. Ultrasonic pulse velocity (UPV)

The UPV test was determined according to the TS EN 12504-4 standard (TS EN 12504-4, 2004). Ultrasound velocity measurement was made with an ultrasound measuring instrument with a digital display. Before starting the measurements, the device was calibrated each time. Vaseline was applied to the sample surface to prevent any gaps between the probes and the concrete sample. The transmission time of the sound through the concrete sample was determined by placing an ultrasound transmitter on one end of the concrete sample and a receiver receiving the sound waves passing through the material at the other end. From here, the propagation speed of sound was found (Saint-Pierre et al., 2016). Ultrasound test was applied to 3 samples from each of 9 different concrete series, including samples subjected to carbonation before carbonation, 1 day, 3 days and 7 days carbonation. Two readings were taken from the 4 side surfaces of the samples prepared for the experiment. The averages of the measured data of each series were recorded as the sound waves transmission time of that series.

2.4.4. Porosity test

The porosity test was determined according to the TS EN 772-4 standard (TS EN 772-4, 2000). The porosity determination test was applied to 3 samples from each of 9 different concrete series, which were cured in lime-saturated water for 28 days, using a porosity measuring scale. The porosity value was obtained by using the formula given in Equation 2 (Safiuddin and Hearn, 2005). The averages of the data obtained as a result of this experiment were recorded as the porosity value of that series.

$$P=\frac{W_{ssd}-W_{dry}}{W_{ssd}-W_{water}}*100 \tag{2}$$

P : Porosity (%)
W_{ssd} : Saturated surface dry weight of samples (kg)
W_{dry} : Oven-dry weight of samples (kg)
W_{water} : Weight of samples under water (kg) (TS EN 772-4, 2000).

2.4.5. SEM observations

In the study, the microstructure of AS concrete was investigated using scanning electron microscopy (SEM). In the SEM images, the formation of wider cracks, openings and interfacial voids in the concrete matrix was observed with the addition of AS (Figure 3).

When Figure 3 (a) is examined, despite the x50 magnification, no obvious cracks were observed in the micro image without AS. When Figure 3 (b) is examined, it is understood from the micro-image of the sample that the adherence due to the use of sawdust is not complete, and from the trace left by the AS peeling off. In addition, microcracks are clearly visible.

2.4.6. Accelerated carbonation experiment

The carbonation depth was measured in accordance with the BS EN 13293-2004 standard (Safiuddin and Hearn, 2005). For carbonation to take place, sodium dichromate was chosen for 55% humidity at 20 °C (Figure 4) (Gönen and Yazıcıoğlu, 2005). The saturated solution of sodium dichromate was placed in the water container inside the tank and the temperature of the water was kept at 20 °C throughout the experiment. The samples were placed in the tank at regular intervals and with no surfaces touching each other, and the lid of the tank was tightly closed so that there would be no gas leakage. 40% CO_2 was given into the tank from the CO_2 filled tube via a one-way valve. In 9 different concrete series, the samples were exposed to carbonation according to different time periods as 1 day, 3 days and 7 days.

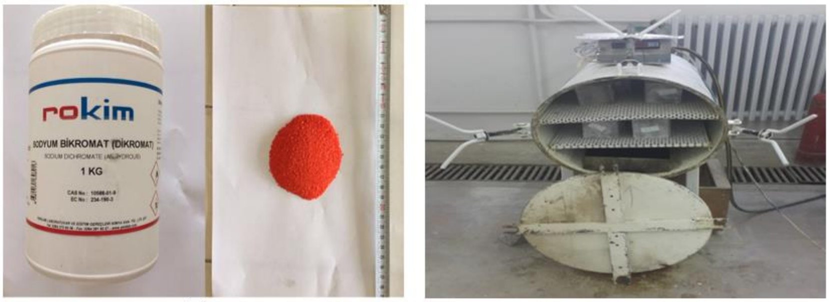
Compressive strength, splitting tensile strength, ultrasound and porosity tests were performed on the samples removed from the carbonation tank. The samples, which were divided into two after the split tensile test, were cleaned from the dust and particles on the surface, and then 1% phenolphthalein ($C_2OH_{14}O_4$) - 70% ethyl alcohol solution was sprayed. It reacted with phenolphtalein and its hydration product, $Ca(OH)_2$ and dyed that area pink, and no color change was observed in the carbonation parts of the samples. Depths of parts that do not change color on concrete samples As seen in Figure 5, it was measured from 8 different places and carbonation depth was determined using Equation 3.

$$D = \frac{A_1 + A_2 + B_1 + B_2 + C_1 + C_2 + D_1 + D_2}{8} \tag{3}$$

D : Average carbonation depth (mm)

A,B,C : Carbonation depth of each surface.

The results of pre-carbonation (free carbonation) and post-carbonation compressive strength, splitting tensile strength, ultrasound transmission velocity and porosity tests are summarized in Table 3.



(a) (b)

Figure 4. (a) Sodium bichromate salt (b) Gas-leakproof tank used for carbonation test.

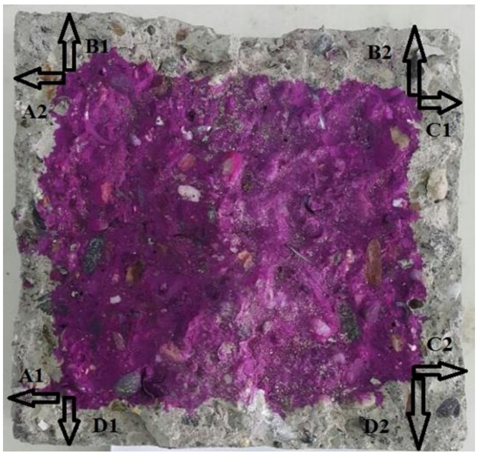


Figure 5. Carbonation depth measured at the sample surface.

Table 3. Test results of concrete series containing various percentages of AS

Mixture Code			0.4AS0	0.4AS5	0.4AS10	0.5AS0	0.5AS5	0.5AS10	0.6AS0	0.6AS5	0.6AS10
Compressive strength (MPa)	Free Carbonation		67.78	49.15	39.03	53.34	40.09	36.58	37.19	36.1	34.91
	Carbonation days	1	68.65	50.92	40.36	56.06	41.02	36.97	41	38	36.37
		3	69.14	51.03	41	56.1	42.56	39.21	41.84	39	37.56
		7	69.8	57.23	46.08	57.84	45.99	40.76	43.55	42	39.7
Split tensile strength (MPa)	Free Carbonation		3.8	2.65	2.43	3.38	2.57	2.41	3	2.5	2.25
	Carbonation days	1	3.93	2.96	2.58	3.43	2.94	2.84	3.08	2.5	2.38
		3	4.35	3.19	2.75	3.55	3.12	2.85	3.14	2.67	2.4
		7	4.75	3.58	2.99	4.12	3.3	2.91	3.2	2.9	2.87
Ultrasonic pulse velocity (km/sec)	Free Carbonation		4.85	4.66	4.55	4.44	4.37	3.91	4.42	4.28	3.89
	Carbonation days	1	4.82	4.77	4.55	4.32	4.2	4.16	4.38	4.3	4.09
		3	4.98	4.73	4.54	4.38	4.25	4.13	4.44	4.3	4.07
		7	5	4.8	4.65	4.66	4.36	4.33	4.5	4.35	4.16
Porosity test (%)	Free Carbonation		6.03	6.9	7.19	11.53	14.96	14.99	12.46	17.55	18.14
	Carbonation days	1	7.4	12.16	11.49	11.75	14.49	14.17	14.15	16.28	17.27
		3	8.34	11.35	12.48	11.25	14.39	14.11	13.8	15.1	16.51
		7	7.35	10.48	11.3	11.26	14.34	14.09	14.5	15.3	15.95

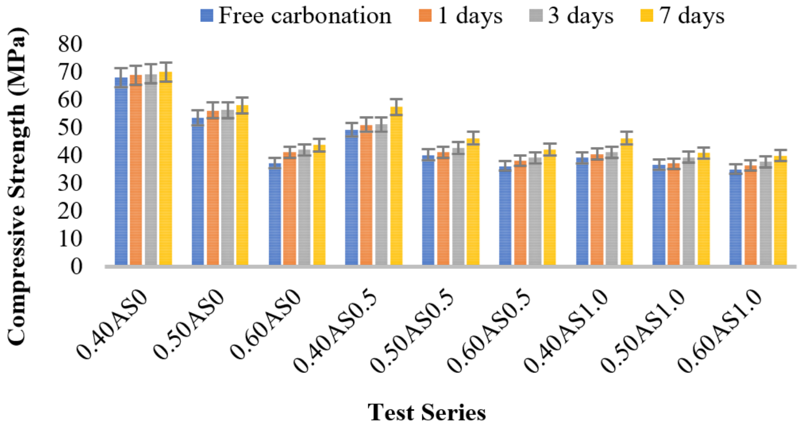


Figure 6. Relationship between compressive strength-carbonation curing ages.

3. Results and Discussion

3.1. Compressive Strength

The compressive strength values of the prepared series, with and without AS were determined according to the different curing times before and after the carbonation test (Figure 6). In accordance with the literature, the time-dependent compressive strength value increased as expected. However, with the increase of AS amount, the compressive strength value decreased. Due to AS particle sizes, it could not fully settle in the mortar and created voids, and at the same time, it negatively affected the workability of the concrete. Therefore, it was concluded that the compressive strength of concrete also decreased. Seyed; In his study with steel fiber, he mentioned that the steel fiber additive affects the workability of concrete negatively and reduces the compressive strength (Gupta et al., 2016). The changes in the compressive strength values of the series without AS and with 0.5% AS, with a W/C ratio of 0.40-0.50-0.60 before carbonation, are 27.37%, 24.84% and 2.93%, respectively. On the other hand, the compressive strength value of the series exposed to carbonation for 7 days increased by 2.89% compared to pre-carbonation. This shows that carbonation has a positive effect on the compressive strength of concrete.

With the emergence of $CaCO_3$, which is the product of the carbonation reaction in concrete, an increase in density occurred in the carbonated parts and this density increase on the surface showed itself with a slight increase in strength. This situation is also compatible with the literature. Erdogan (2003) stated that the water released as a result of the carbonation event may cause some increase in strength by helping the hydration of the cement.

3.2. Split Tensile Strength

The comparison of the splitting tensile strength values of the prepared test series was determined according to the different curing times before and after the carbonation test, with and without AS (Figure 7).

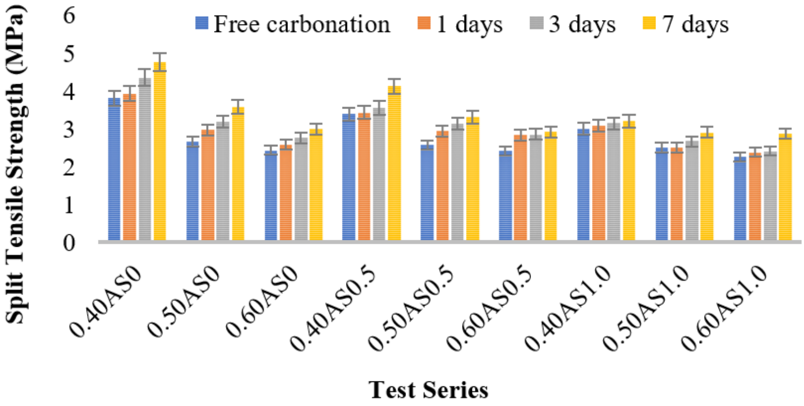


Figure 7. Relationship between split tensile strength-carbonation curing ages.

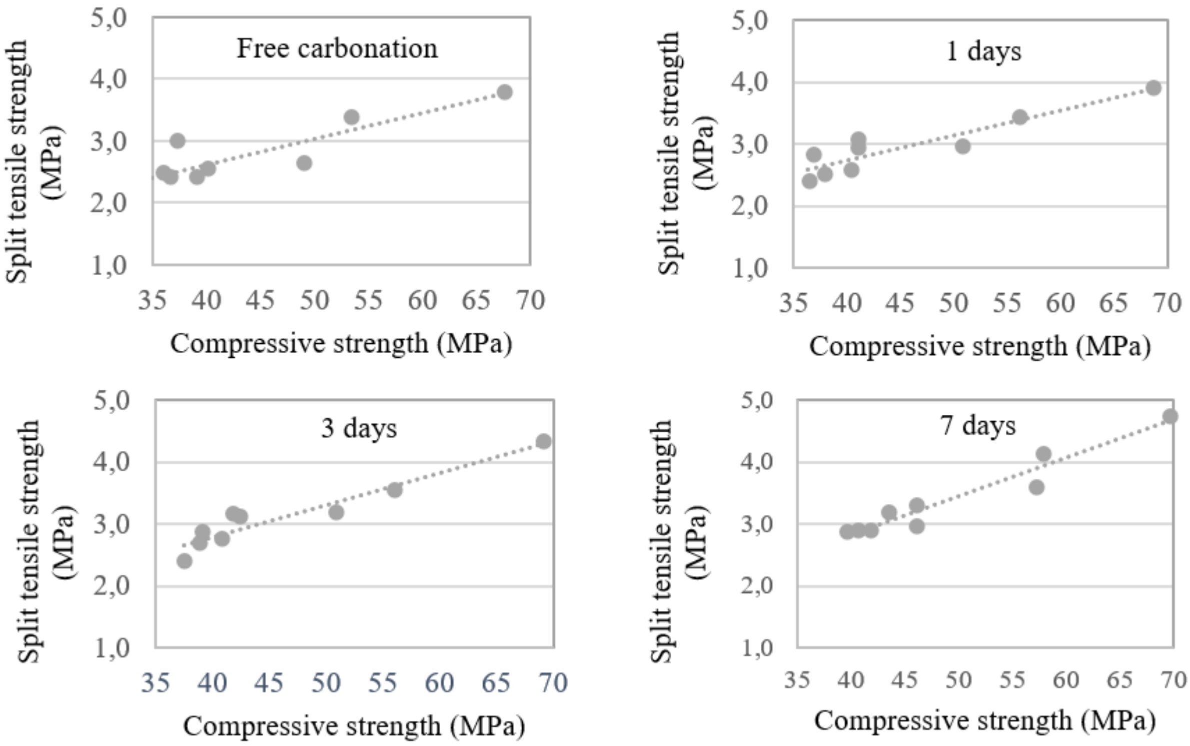


Figure 8. Relationship between compressive strength and split tensile strength of all test series.

In Figure 7, when the concrete samples exposed to carbonation for 7 days were examined, the split tensile strength values increased between 6.65% and 34.68% compared to the control samples. Among the samples exposed to carbonation for 7 days, the highest splitting tensile strength is seen in 0.4AS0 concrete samples, and the lowest splitting tensile strength is seen in 0.6AS10 concrete samples. It is seen that the most suitable ratio for the concrete series containing AS, which has been exposed to carbonation for 7 days, is the 0.4AS5 concrete series. In summary, it is seen that the splitting tensile strength of the concrete mixtures containing AS is lower than the concrete mixtures without AS at all curing ages, and the splitting tensile strength decreases due to the voids formed as the amount of AS increases.

When the comparison of compressive strength and splitting tensile strength values is examined in Figure 8, split tensile strength values increase in parallel with the compressive strength in accordance with the literature.

3.3. Ultrasonic Pulse Velocity (UPV)

When Figure 9 is examined, the highest ultrasound transmission rate in the control series is seen in the 0.4AS0 series, and the lowest ultrasound transmission rate in the 0.6AS10 series. It was determined that the most suitable ratio for the concrete series containing AS that was not exposed to carbonation was the 0.4AS5 series.

In Figure 9, there was an increase of approximately 3% between the control series and the 7-day ultrasound transmission rate values. It was determined that carbonation increased the ultrasound transmission rate. $CaCO_3$, which is formed as a result of carbonation, reduces the permeability and creates a structure with less voids in the concrete. Thus, as the ultrasound waves propagate faster in the concrete, the ultrasonic transmission velocity values increased due to carbonation.

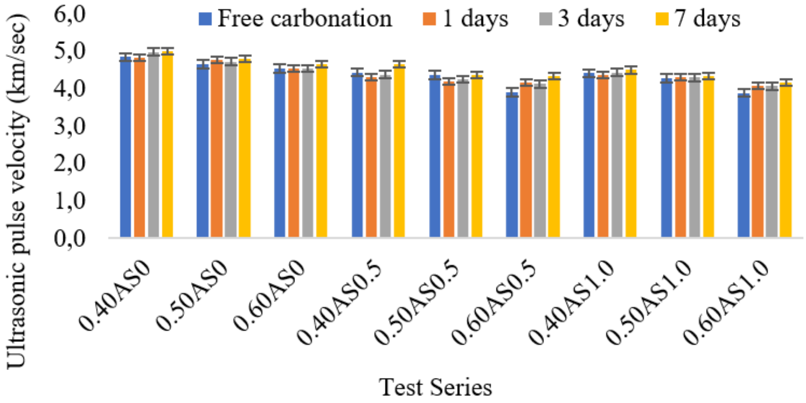


Figure 9. Relationship between ultrasonic pulse velocity-carbonation curing ages.

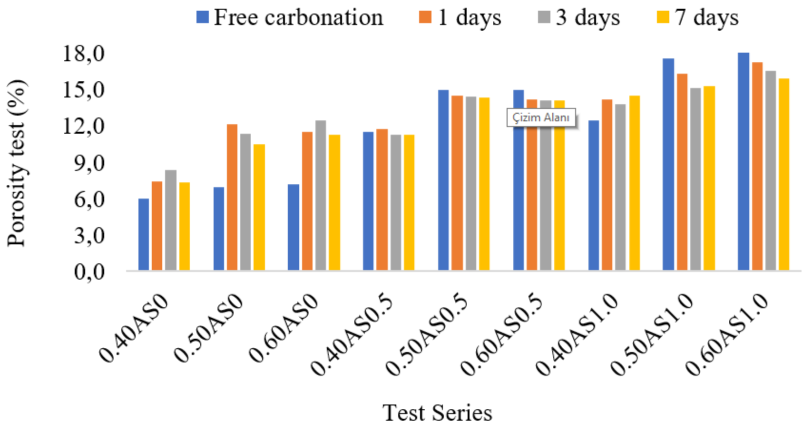


Figure 10. Relationship between porosity-carbonation curing ages.

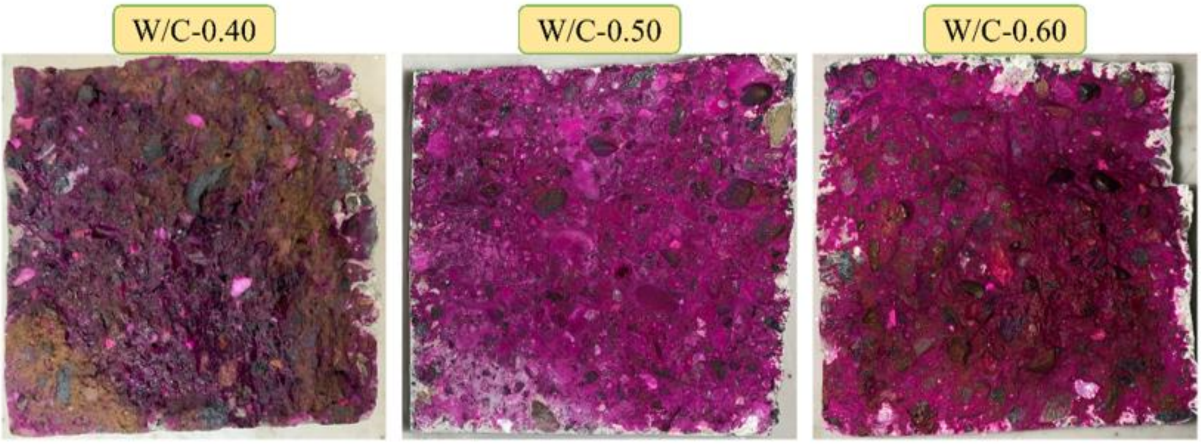


Figure 11. Carbonation depths of series with different W/C ratios after 7 days of carbonation (mm).

3.4. Porosity Test

Porosity test results of control series and 1, 3, 7-day series presented at Figure 10. Among the control series, the highest porosity rate was observed in the 0.6AS10 series, and the lowest porosity rate was observed in the 0.4AS0 series. It is seen that the porosity increases as the AS ratio and W/C ratio increase. Calcium carbonate, which emerges as a product of carbonation, occupies more space than calcium hydroxide, thus reducing the porosity of carbonated concrete (Cauberg et al., 2010; Tafraoui, et al., 2016).

The CO_2 penetrating into the concrete and the $Ca(OH)_2$ that comes out with the hydration of the calcium silicate components in the cement react to form $CaCO_3$ (calcium carbonate), which is larger in volume. Increasing the amount of voids in the concrete means more CO_2 entering the concrete. This causes the formation of more $CaCO_3$ (calcium carbonate) and increases the depth of carbonation. When Figure 11 is examined, it is seen that the carbonation depth increases as the W/C ratio increases. The reason for this is that excess water creates a hollow structure in the concrete and facilitates the entry of CO_2 into the concrete, causing more $CaCO_3$ (calcium carbonate) to form (Brandt, 2005).

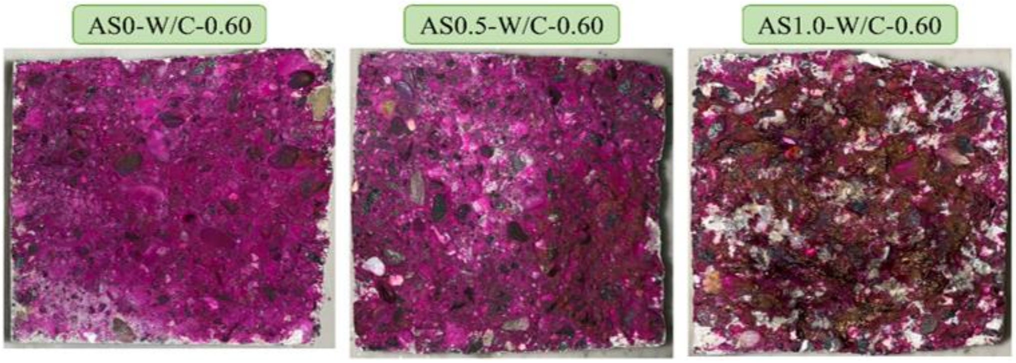


Figure 12. Carbonation depths of series with different sawdust ratios after 7 days of carbonation (mm).

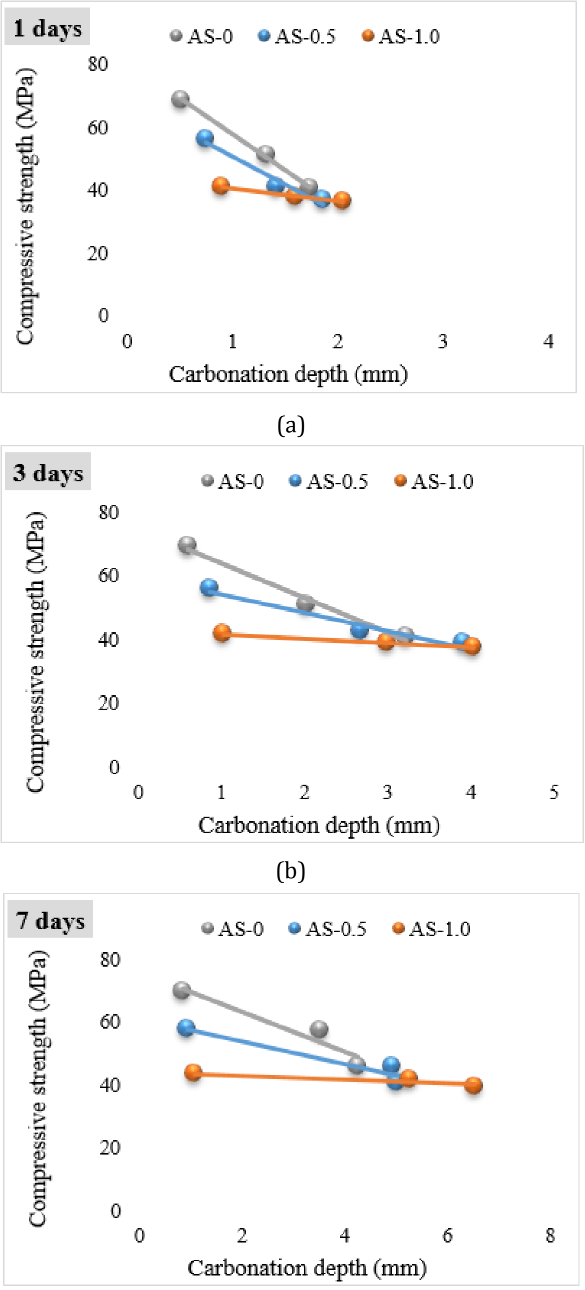
As can be seen in Figure12, the increase in sawdust rate causes an uneven distribution in carbonation. Since the increase in the amount of sawdust makes it difficult for the concrete to settle, gaps have occurred in the parts where the sawdust is concentrated. These gaps facilitated the progression of CO_2 into the interior of the concrete. For this reason, the carbonation event not only occurred on the outer surface of the concrete, but also affected the inner parts of the concrete.

The relationship between compressive strength and carbonation depth is shown in Figure 13. When Figure 13 is examined, it is observed that the compressive strength value decreases with increasing carbonation depth. As the compressive strength increases, the permeability of concrete decreases. As a result, the CO_2 required for carbonation cannot easily penetrate the concrete and the amount of carbonation decreases (Erdogan, 2003). When the comparison is made according to the amount of AS, the compressive strength values of the series containing AS were higher.

3.5. Environmental Impacts with Life Cycle Assessment (LCA)

In this section, it is aimed to determine the environmental and economic effects of the concrete samples produced. According to the International Standard ISO 14044, one of the techniques for analyzing the environmental impact of manufactured products is the life cycle assessment (LCA) (Wang et al., 2017; Dong, 2018; Jain et al., 2020). With the LCA, it is possible to estimate the magnitude of environmental impacts. In this context, Energy Consumption (EC), Global Warming Potential (GWP) and Waste Generation (WG) were taken into account (Table 4). The flow chart of the life cycle prepared for this purpose is given in Figure 14.

When the feasibility of using waste materials in concrete is investigated, many advantages are provided in terms of sustainability, efficient use of natural resources, and reduction of the number of transportation required for the transportation of aggregates, by reducing the use of natural aggregate and replacing it with waste material. However, when the use of AS as a waste material in concrete is evaluated in terms of EC, GWP and WG, higher energy consumption has emerged in concretes with AS added. Parallel to this, the GWP and WG values also showed the same trend (Figure 15).



(c)

Figure 13. Relationship between compressive strength-carbonation depth (a) 1 days (b) 3 days (c) 7 days.

Table 4. Environmental impacts for process

Process	Energy Consumption (MJ)	Global Warming Potential (g CO_2 eq)	Waste Generation (kg)
Cement production (per kg)	3.9854	881.987	
Cement transport (per km.kg)	1.5409	114.286	
FA production (per kg)	0.0219	2.108	-1
FA transport (per km.kg)	1.5409	114.286	
NA production (per kg)	0.0219	2.108	-1
NA transport (per km.kg)	1.5409	114.286	
Concrete production (per m^3)	20.0689	6529.676	

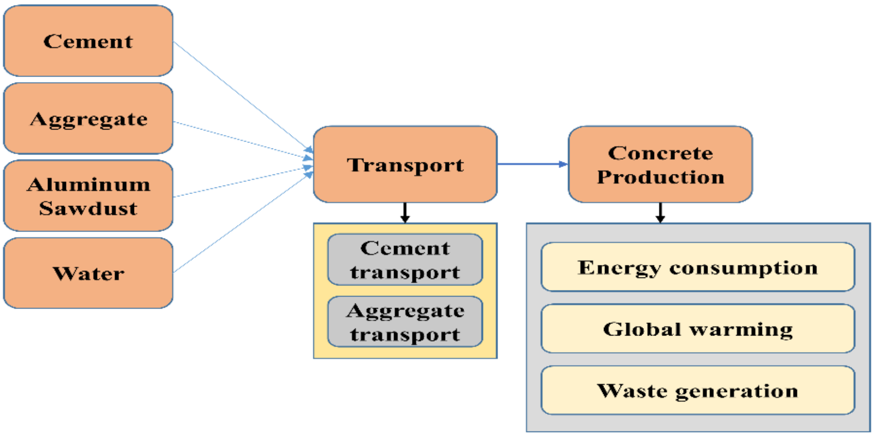


Figure 14. Environmental assessment of the concrete production process by LCA.

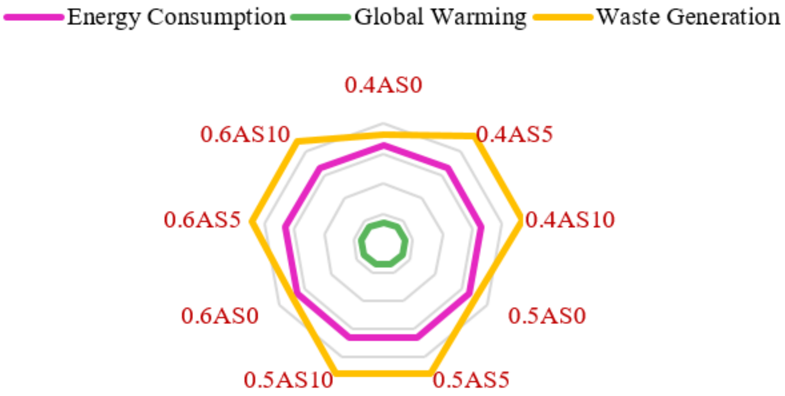


Figure 15. Life cycle results.

4. Conclusion

In this study, the changes in the mechanical properties of the concrete mixtures produced using different AS ratios in 3 different carbonation time periods and the environmental evaluation of these concretes were investigated. The findings obtained as a result of the study are given below in substances.

1. The highest increase in the compressive strength value after carbonation is observed in the 0.4AS5 series, and this increase is approximately 16%.
2. Since the homogeneous distribution of AS in the concrete mixture cannot be achieved, the workability of the concrete series with AS has decreased. As a result, the compressive strength of concrete was adversely affected. On the other hand, splitting tensile strength of AS added concrete series increased despite the negative workability. The reason for this is that AS acts as reinforcement in the mortar and prevents the formation of cracks. Therefore, the use of AS in concrete up to a certain rate has a positive effect.
3. After a certain amount of AS, there was a decrease in compressive strength, splitting tensile strength and ultrasound transmission rate, while an increase in porosity and carbonation depth was observed. As with all other waste materials, the use of waste material above a certain rate adversely affects the mechanical properties of concrete.
4. In all series, as the number of days exposed to carbonation increased (from 0 to 7 days), the compressive strength, splitting tensile strength and ultrasound transmission velocity values increased in parallel with the carbonation depth.

The most significant increase was observed in the 0.4AS5 series. This situation shows the suitability of the use of AS in concrete, its usability in terms of economy and sustainability. On the other hand, when the evaluation was made within the scope of LCA, there was an increase in EC, GWP and WG values in the use of AS.

5. Further research will be conducted to determine the effect of waste materials on carbonation and mechanical properties of concrete. Mechanical properties and structural behavior after cracking will be evaluated. In addition, the environmental impact of the use of waste materials in concrete will be evaluated, the positive and negative contribution of waste materials will be determined and comprehensive studies will be carried out on their use in concrete.

Author Contributions

The percentage of the author(s) contributions is presented below. All authors reviewed and approved the final version of the manuscript.

	T.D.	B.D.	M.Ö.
C	40	50	10
D	40	50	10
S	50	40	10
DCP	40	40	20
DAI	40	40	20
L	30	30	40
W	60	30	10
CR	40	50	10
SR	60	30	10

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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