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Enhancing Self-Compacting Concrete Performance by Substituting Fine Limestone with Wood Ash

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ABSTRACT

This work falls within the scope of waste valorization and reuse, specifically agricultural and vegetal waste, in the formulation of self-compacting concrete (SCC) which mainly consist of limestone fines. The production of these fines requires energy consumption and negatively impacts the environment. Partial replacement of these fines with wood ash, which is generated in large quantities from forest incineration, combustion of vegetal waste, and charcoal preparation, becomes a solution to reduce the production cost of these fines and preserve the environment. The study involved creating reference SCC with no wood ash, then replacing the fine limestone with wood ash in volumes of 6.12%, 18%, and 24%, and analyzing the properties of the resulting concrete in both fresh and hardened states. Tests included density, slump flow, L-Box, segregation resistance, V-funnel, air content, compressive strength, flexural tensile strength, sclerometer resistance, ultrasonic pulse velocity, and elastic modulus, as well as analysis by DRX and FTIR. The findings indicate that partial replacement of fine limestone with wood ash improves the compactness and stability of the concrete, and reduces spreading, particularly in a confined environment. Additionally, the study shows that the SCC with wood ash substitution meets the European standard EFNARC and exhibits acceptable mechanical performance.

1. INTRODUCTION

Wood ash, a common by product of burning wood in a fireplace, wood stove, or biomass power plant, is a sustainable option for concrete that repurposes waste material, reducing disposal needs and environmental impact, while potentially conserving resources. It is often low-cost or free, making it a cost-effective choice.

It is a fine grayish powder that is rich in minerals, some of the latter are valued by spreading on agricultural land [1] as fertilizers or calcium amendments, although they do not provide enough nutrients to be applied for this purpose [2]. The other part is usually deposited in landfills, which quickly become numerous and over time constitute an environmental burden. Particular attention is then paid to this niche bringing added value in order to consider the recovery of these ashes in building materials for a circular economy; in a context of sustainable development.

In this same, thinking about the recovery of these ashes as an addition in the formulation of a self-compacting concrete can be an economical solution because this material consists essentially of fine limestone and fillers, and that the production of these latter requires a lot of energy and has a negative impact on the environment. The use of ash from vegetation (coal ash, wood ash, palm ash, cane bagasse ash, rice husk ash, olive pomace ash, ...) has been the subject of numerous research due to the pozzolanic and/or hydraulic activity of these ashes [3].

Mohammadhosseini et al. [4] investigated the replacement of cement in self-compacting concrete (SCC) with palm oil fuel ash. They found that the fresh state properties of the SCC met the standards and improved with increasing ash content. The compressive strength increased with more ash, while the flexural strength was still lower than that of the reference SCC.

Bhat [5] conducted a study to examine the impact of partially replacing cement with coal ash and wood ash on the mechanical performance of a SCC. The results showed that substituting 10% of the cement with these ashes resulted in resistances that were comparable to the reference SCC, the use of wood ash and coal ash in self-compacting concrete (SCC) has advantages such as waste utilization, reduced cement quantity, and sustainability. However, there are shortcomings in terms of strength reduction, lack of comprehensive environmental assessment, cost implications, lack of standardized guidelines, and durability considerations. Further research is needed to optimize the use of wood ash and coal ash in SCC and ensure its practical viability. Olatokunbo et al. [6] investigated the effects of different levels of self-compacting lightweight concrete when cement was partially replaced with palm ash (10-50%). They found that the optimal replacement rate that provided satisfactory resistances was 20%.

In the study conducted by Moretti et al. [7], the feasibility of replacing a portion of the cement in self-compacting concrete with sugar cane bagasse ash was investigated. The results showed that for a substitution rate of 30%, the impact of ash on the fresh SCC and its resistivity was negligible, possibly due to its low pozzolanic activity, however, they concluded that these findings were suitable for various civil engineering applications and met the necessary standards. Tayyeb et al. [8] aimed to lower the cost of producing self-compacting concrete by using sugar cane bagasse ash as a viscosity modifying agent. The cost of the ingredients was evaluated, and the results showed that producing self-compacting concrete with bagasse ash is a feasible and cost-effective option. The fresh state properties of the concrete were found to be acceptable and the compressive strengths at 28 days were comparable to those of the control concrete. Additionally, the cost of materials in the bagasse ash self-compacting concrete mixture was 35-63% lower than that of the control concrete.

Gritsada and Makul [9] carried out an investigation into the replacement of some of the fine aggregates in self-compacting concrete with bagasse ash and fine limestone. They discovered that replacing these components in the fine aggregates leads to a reduction in density and an improvement in fluidity. However, the mix with a 40% replacement rate showed blockage. The addition of 20% ash, due to its filling effects and pozzolanic processes, enhances the mechanical properties.

In their research, Hasnain et al. [2] investigated the impact of replacing the sand in self-compacting concrete with a combination of rice husk ash and bagasse ash. They evaluated the effects on fresh properties, physical and mechanical characteristics, sulphate resistance, and microstructure. They found that the porous structure of the added ashes impacted the liquidity of the mixtures, causing an increase in viscosity. The results showed that adding 20% ash improved the compressive strengths and densities, with values of 20 MPa and 1816 Kg/m^3, respectively. Additionally, the pozzolanic reaction increased the sulphate resistance of the self-compacting concrete and led to the formation of a secondary C-S-H gel, the resulting values are still within the appropriate limits for structural applications.

The study conducted by Cuenca et al. [1] explored the use of fly ash from the burning of olive pomace grains as a filler in self-compacting concrete the results showed that the material had strong self-compacting properties and adequate mechanical strengths, further research, standardization, and consideration of environmental factors are needed to fully understand its potential advantages and limitations. Elinwa et al. [10] also studied the properties of self-compacting concrete containing sawdust ash. They found that adding 10% of these ashes to cement improved its fresh state properties and compressive strength. Sawdust ashes were found to slow the cement hydration reaction and prolong the setting time by reacting with Ca(OH)2 produced during cement hydration to form a secondary C-S-H gel. The microstructure of the cement paste matrix is improved by this gel and therefore gives dense structure.

All these research works show the importance of the recovery of ash from vegetation as additions replace cement or fine aggregates in the formulation of self-compacting concrete. This research aims understanding the specific effects of wood ash on the properties of SCC, such as its workability, strength, durability and other performance characteristics. Thereby, this may contribute on finding sustainable, cost-effective, and performance-enhancing alternatives in SCC production while reducing environmental impacts for recycling wood ash waste and the limestone which has a negative effect in extraction and energy consumption. Overall this study results in advantageous changes in their properties, offering a promising solution for reducing the dependency on limestone fines in the future which enableus to implement it in practice due to the lack of cost and technical considerations.

2. USED MATERIALS

The materials used in this study are local materials;

- CEM I 42.5, cement from the M'Sila-Algeria cement plant.
- The wood ash (Wa) is produced through the burning of fruit tree cuttings, sawdust, and harmful plants by farmers without any further processing. Afterward, the ash is sifted to remove impurities and obtain a refined product that is free of any unwanted coarse particles.
- Fine limestone (L) from the Ben-Azzouz Skikda quarry, eastern Algeria.
- A class (0/3) crushed limestone sand (S) from the Ben Brahim Constantine quarry, eastern Algeria.
- Crushed limestone gravels of class (G3/8, G8/15) from the Ben Brahim Constantine quarry, eastern Algeria.
- A super high water-reducing plasticizer (SP) of the Master Glenium 3080 type with a brown colour.
- Mixing water (W) from the tap.

The particle size distribution of cement (CEMI), fine limestone (L) and wood ash (Wa) is given in the Figure 1.

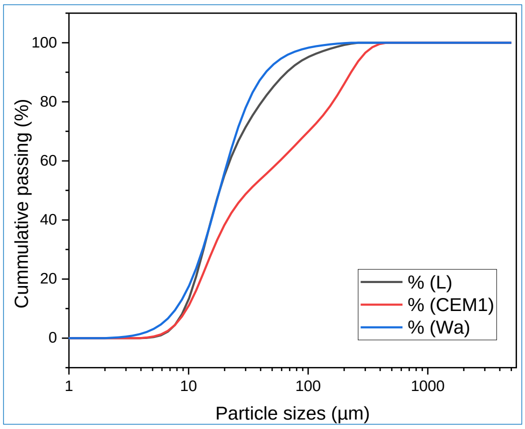

Figure 1. Particle size distribution of cement, limestone and wood ash

According to the material characterization tests, it can be concluded that:

- The Figure 1 indicates that the three curves are extended smoothly and exhibit a favorable particle size distribution, with wood ash being finer compared to limestone fines and cement, respectively. It can be inferred that the incorporation of wood ash enhances the compactness of (SCC).
- Wood ashes have a very low absolute density in comparison with fine limestone, which implies that the substitution of these fines by ash makes the concrete lighter.
- The specific surface of wood ashes shows that its fineness is greater compared to fine limestone this property can effect on the water demand and the density.

The results of the structural study by XRD of cement, fine limestone and wood ash are given in Figure 2.

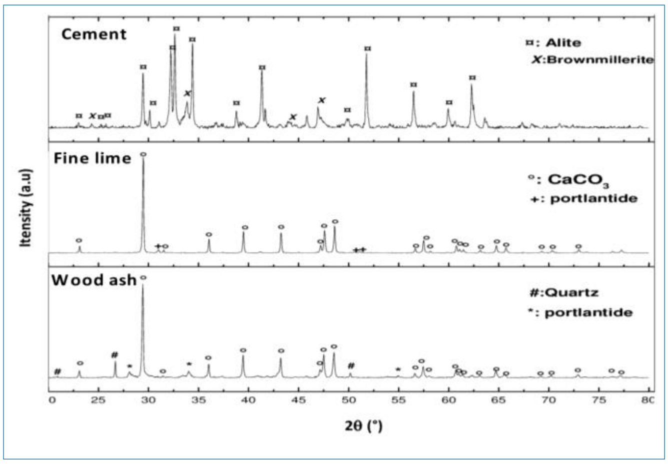

Figure 2. XRD patterns of Portland cement, fine limestone and wood ash

The wood ash spectrogram (Figure 2) displayed a crystal structure with sharp peaks and a horizontal baseline. The existence of quartz and calcium carbonate ($CaCO_3$) as major phases and Portlantide as minor phases has been identified in this material. When used as an additional binder in conjunction with Portland cement, the calcium carbonate mineralogical phase can act to accelerate the process of hydration of the C3S mineralogical phase present in Portland cement [11, 12]. This mechanism aids in the cementitious mixture including wood ashes quickly gaining strength at the early age of hydration. Additionally, wood ash, which is high in Portlandite and the mineral, can be employed effectively in conjunction with silica-rich powder. An early injection of Portlandite is introduced to speed up the development of the C-S-H gel via a subsequent hydration reaction. The presence of these chemical phases is consistent with the results of the X-ray fluorescence study presented in Table 1.

Table 1. Chemical and physical composition properties of used cement, fine limestone and wood ash

Raw material	CEM I	L	Wa
Specific gravity g/cm^3	2.99	2.74	2.33
Specific surface area cm^2/g	2343	3526	4244
CaO (%)	62.85	55.80	32.01
S_iO_2 (%)	21.01	0.14	10.16
Al_2O_3 (%)	5.02	0.01	1.10
Fe_2O_3 (%)	3.14	0.01	1.10
MgO (%)	1.85	--	8.30
SO_3 (%)	2.04	--	--
K_2O (%)	0.45	--	--
Na_2O (%)	0.11	0.01	--
Cl^- (%)	0.017	0.21	--
Loss on ignition	1.78	--	40
C_3S	61.00	--	--
C_2S	14.50	--	--
C_3A	02.40	--	--
C_4AF	15.22	--	--

The chemical studies (Table 1) show that the amount of CaO in the wood ashes is approximately 32.01% lower than that in the fine limestones, suggesting that the wood ashes may be hydraulically reactive [13].

- The content of silica SiO_2 is 10.16%, the presence of this element can increase the strength of concrete in the long term.

- Other substances, namely SO_3, Fe_2O_3, MgO, Na_2O and Al_2O_3, were detected in trace quantities.

- The high content of organic matter in the ash (loss on ignition equal to (40%) this most likely results from the partial heat breakdown of the calcium carbonate phases into calcium oxide and the subsequent release of carbon dioxide [14] increases the water demand and decreases the majority of oxides and affects the pozzolanic reaction [15].

3. EXPERIMENTAL PROGRAM

The goal of this study is to value and assess the advantages of employing wood ash as a fine limestone substitution in the composition of a self-compacting concrete at rates varying from 0 to 24% with a pat by 6%, represented in the Table 2. The reference SCC was formulated by the LGC method proposed by Shen et al. [16]. This method makes it possible to optimize the compaction of the aggregates and ensures good fluidity of the SCCs with the fixed parameters being the ratio W/L=0.43 and G/S=1. The other formulations were obtained by the same method, replacing the volume of fine limestone with volumes of wood ash.

Table 2. Composition of mixtures

Concrete	CEMI Kg	L Kg	Wa Kg	SP L	W L	S 0/3 Kg	G 3/8 Kg	G 8/15 Kg
C(0%)	442	80	0	7.8	229	816	429	419
C(6%)	442	75.2	4.8	7.8	229	816	429	419
C(12%)	442	70.4	9.6	7.8	229	816	429	419
C(18%)	442	65.6	14.4	7.8	229	816	429	419
C(24%)	442	60.8	19.2	7.8	229	816	429	419

The tests carried out on SCC in the fresh state are:

- Slump flow test measured by the Abrams cone according to standard NF EN 12350-8.
- Passing ability (L –Box) compliant with standard NF EN 12350-10.
- Segregation resistance (Segregation index) according to standard NF EN 12350-11.
- Filling ability V– funnel according to standard NF EN 12350-9.
- Density measured in accordance with the prescription of standard NF EN 12350-6.
- Air content measured by a concrete aerometer in accordance with standard NF EN 12350-7.

The hardened state testing on the different formulations are detailed below:

- Compressive strength on cubic specimens of dimension 15x15x15 cm^3 at ages 7, 28 and 90 days according to standard NF EN12390-3.
- Flexural tensile strength on prismatic specimens of dimension 7x7x28 cm^3 at ages 7, 28 and 90 days in conformity with NF EN 12390-5 standard.
- Ultrasound test and rebound hammer test on specimens measuring 20x20x20cm^3 in accordance with standards NF EN 12504-4 and NF EN12 504-2 respectively.
- Water absorption by immersion was studied on cubic specimens 10x10x10 cm^3 in accordance with standard NBN B 15-215.
- Water absorption by capillarity on 7x7x28cm^3 test specimens according to standard NF EN 480-5.
- The determination of amorphous and crystalline phases by X-ray diffractions were carried out by an XRD diffractometer (Philips, X'Pert), using Cu Kα radiation at 40 kV, 35 mA with

a step width of 0.02° ranging from 10° to 80°. ICDD maps were used to identify peak intensity and position.

- Sample images using a scanning electron microscope SEM (Tescan Vega3) revealed the microstructure and pore morphology.

A Fourier Transform Infrared (FTIR) spectroscopy examination was additionally carried out utilizing the SHIMATZU model. apparatus in the absorption range 400cm-1 to 1500cm-1.

4. RESULTS AND DISCUSSION

4.1 Properties of fresh SCC containing wood ash

4.1.1 Slump flow test

Figure 3 shows that the partial replacement of fine limestone by wood ash leads to a decrease in the consistency and cohesion of the mixtures as a function of the increase in the rate of substitution, but the diameter of the spread remains within the standards.

This decrease may be due to the higher water demand of wood ash due to the texture and irregular shape of the particles and its porosity [17] and organic matter content [18-20].

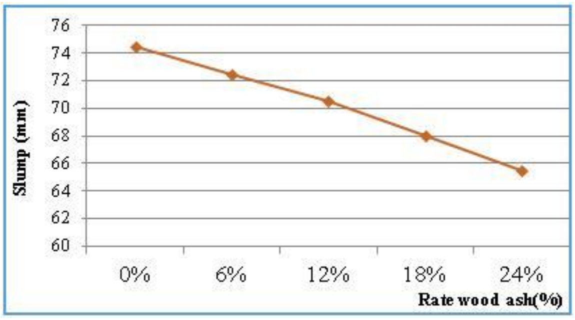

Figure 3. Influence of substitution rate on flowability

4.1.2 Passing ability (L–Box)

Verification of the installation of the SCC by mobility in a confined environment (Figure 4), and its ability to cross a heavily reinforced zone shows that the passing capacity increases with the increase in the percentage of ashes up to a rate of 18% or the risk of segregation is minimal, beyond this rate the passing capacity decreases to reach a value of 0.88 at a rate of 24% (higher value of the reference SCC).

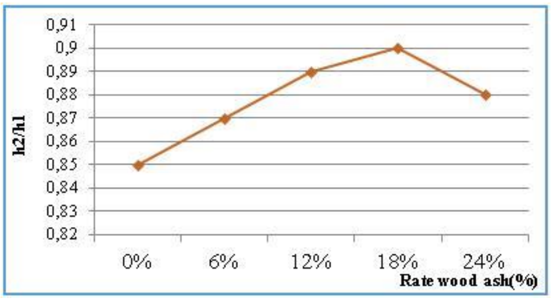

Figure 4. The impact of substitution rate on the passing ability

It can be said that wood ash improves the flow of SCC in a confined environment, and the optimum value is recorded for a rate of 18%. These results do not agree with those found by Muhammad Usman [17].

4.1.3 Segregation resistance (Segregation index)

The segregation index (Figure 5) increases by an insignificant variation with the importance of the wood ash rate but remains below 15% (value recommended by the standard), which translates into satisfactory stability and a low risk of static segregation.

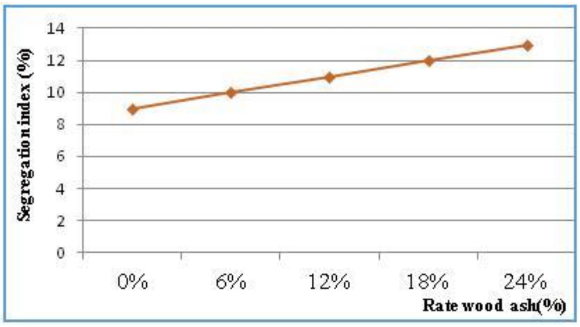

Figure 5. Influence of substitution rate on segregation index

The addition of wood ashes in partial substitution of fine limestone preserved a homogeneous composition under the effect of gravity.

4.1.4 Flow time "V – funnel" filling ability and viscosity

The introduction of wood ash into the SCC formulation causes a reduction in the flow time in comparison with the control SCC (Figure 6) to reach a value of 8 seconds, hence a minimum apparent viscosity, which translates into good workability.

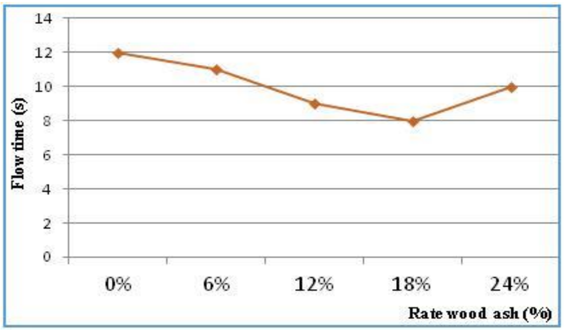

Figure 6. Influence of substitution rate on flow time

The higher organic component of the ash explains these results [21]. However, this characteristic is lost for high substitution values because the water demand will be higher and will generate greater friction between the particles which explains the increase in the flow time has a rate of 24% which remains lower than that of the controls SCC.

4.1.5 Density

The addition of wood ash in the SCC formulation (Figure 7) leads to an increase in density up to a rate of 12%, beyond this rate the effect is reversed.

The angular shape of the wood ashes leads to an arrangement in the internal structure of the SCC and plays the role of filling, which explains the increase in density (0 to 12%) on the other hand for a higher rate (24%) the porosity high and low ash density makes the concrete lighter but denser than the control SCC [22].

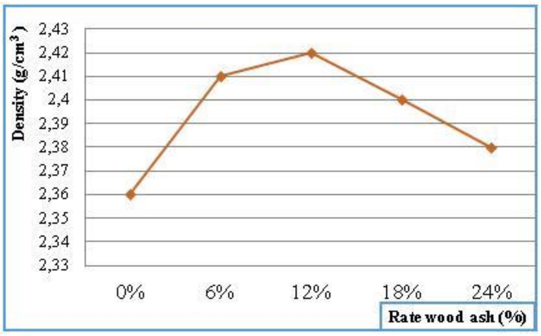

Figure 7. Effect of the substitution rate on the density

4.1.6 Air content

The air content (Figure 8) decreases with the addition of wood ash to reach a minimum value at 12% of substitution rate, this decrease may be due to the angular shape of the wood ash which leads to an arrangement in the internal structure of the SCC and makes its compactness maximum at this rate.

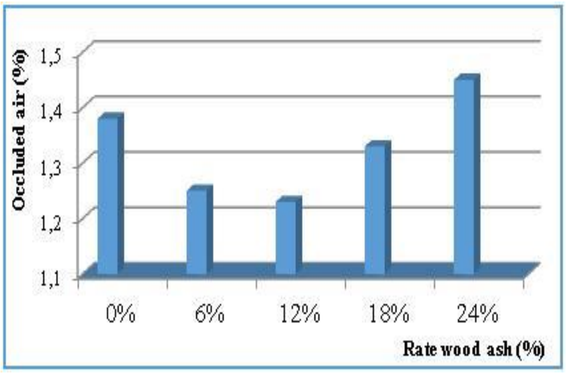

Figure 8. Effect of the substitution rate on the occluded air variation

Beyond 12% of substitution rate, the content of occluded air increases to mark a maximum value of 24%, this phenomenon can be explained by the porosity and the irregular morphology of the particles of wood ash [22, 23].

4.2 Properties of hardened SCC containing wood ash

4.2.1 Compressive strength

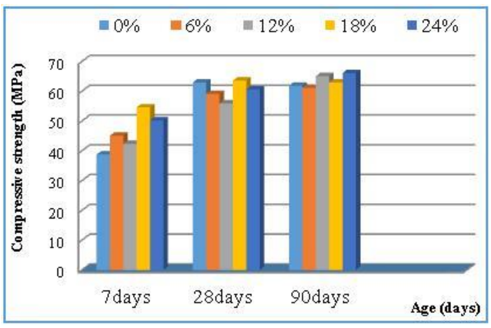

Figure 9. Effect of the substitution rate of wood ash on the compressive strength

Figure 9 shows that mixtures based on wood ash record higher compressive strengths at early age (7 days) compared to the reference SCC.

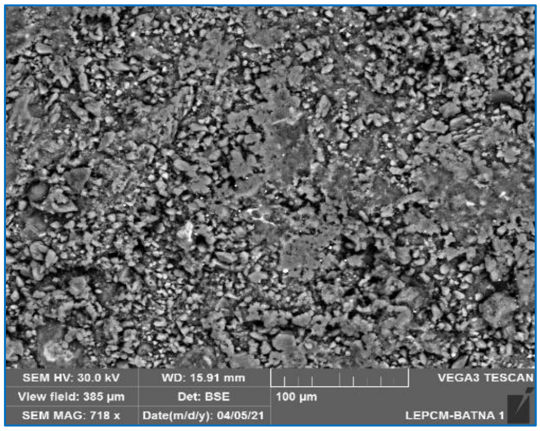

Figure 10. SEM images of SCC with 18% Wa content

These results may be due to the accelerated hydration rate of C3S in the presence of calcium carbosilicate hydrate, which may also contribute to void filling (Figure 10) when adding wood ash [24].

After 28 days of curing, all blends show an improvement in compressive strength and the maximum strength is given by the SCC of 18% substitution rate. In the long term (90 days), the SCCs based on wood ash gave the best compressive strengths in comparison with the reference SCC, these results are explained by the presence of Portlandite which accelerates the formation of the C-S-H gel by a reaction secondary hydration [25, 26] (results confirmed by XRD).

4.2.2 Flexural tensile strength

The behaviour in flexural tensile bending is the same as in compression at a young age, the addition of wood ashes (Figure 11) generates an increase in the tensile strengths by bending which remain acceptable at 28 days.

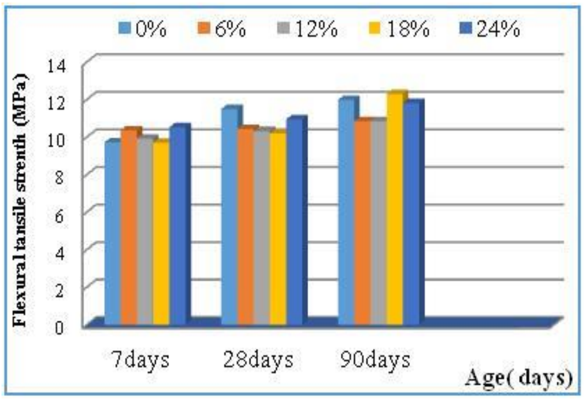

Figure 11. Effect of the substitution rate of wood ash on the flexural tensile strength

In the long term (90 days), the smaller size wood ash particles effectively filled the spaces between the coarser fraction of the aggregate particles as well as the cement particles, which explains the best resistances of 18 and 24%. In addition, the surface roughness of the wood ash grains made a good interlock with the cement paste, leading to a better interfacial transition zone between the aggregate and the paste matrix and thus improved the tensile strength. These results are consistent with those found by Naik et al. [27].

4.2.3. Compressive strength obtained by the rebound hammer tes

The SCCs containing wood ash (Figure 12) have higher surface resistances and hardnesses than the control SCCs alone, this is mainly due to the increase in density by the addition of ashes and to the morphology of the grains which provide better adhesion to dough [17]. The minimum value of the compressive strength is 50.40MPa obtained in the control SCC.

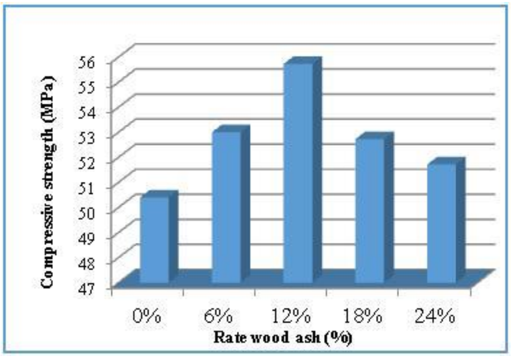

Figure 12. Compressive strength obtained by rebound hammer testing

4.2.4 Ultrasonic pulse velocity

The partial replacement of fine limestone by wood ash in the SCC formulation (Figure 13) significantly influences the homogeneity of the SCCs. SCCs based on wood ash have speeds greater than 4200m/s, which allows these concretes to be classified as very high-strength SCCs [28-30].

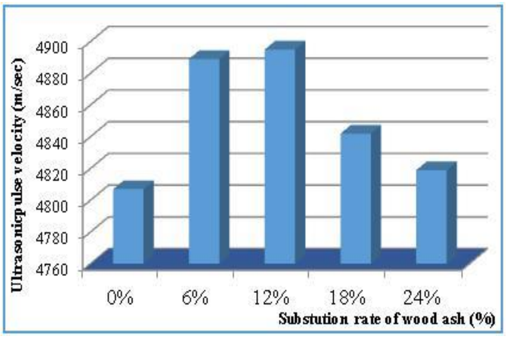

Figure 13. Variation of ultrasonic pulse velocity as a function of substitution rate of wood ash

The speed of sound propagation through the SCCs based on 6 and 12% wood ash substitution rate respectively (4889 and 4895m/s) are faster, in comparison with the control concrete 4807m/s), with an increase from 1.70% to 1.83%. The rapid passage is justified by the increase in the density of mixtures based on wood ash [31] which means that SCCs based on 6 and 12% wood ash are more homogeneous than ashless SCC.

4.2.5 Compressive strength obtained by the combined method

The results obtained by the combined method of non-destructive testing (Figure 14) confirm that SCCs based on wood ash give millstones compressive strength with a maximum value recorded for a rate of 12%. The partial substitution of fine limestone by wood ash makes the structure of the SCC more compact than the control SCC [29].

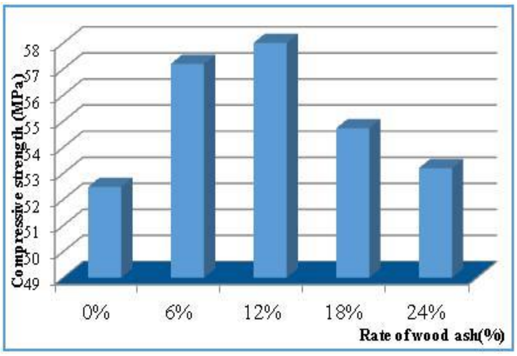

Figure 14. Influence of the substitution rate on the compressive strength obtained by combined method

4.2.6 Elastic modulus

The dynamic modulus of elasticity (Figure 15) increases with the increase in the rate of substitution of fine limestone by wood ash with a variation ranging from 3.75% to 5.83% for a rate of 18%. Wood ashes have a positive effect on the modulus of elasticity of concretes which is due to the increase in the adhesiveness of the interfacial transition zone, cement paste/fine aggregates [25].

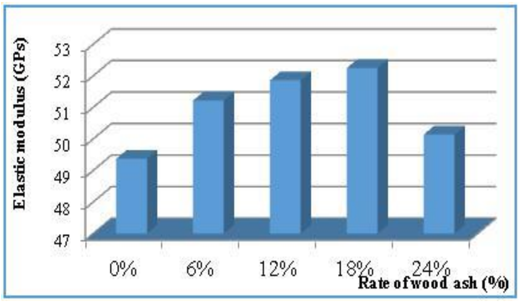

Figure 15. Relationship of elastic modulus with wood ash content

4.3 Durability properties of SCC

4.3.1 Water absorption by immersion

The absorption of water by immersion (Figure 16) decreased with the increase in the rate of substitution of wood ash compared to control SCC. This decrease is related to the decrease in entrained air and the increase in density.

The wood ash particles have an angular shape which leads to an arrangement in the internal structure of the SCC and makes its maximum compactness [22]. These results are consistent with the results found by Raza et al. [32] and Memon et al. [33].

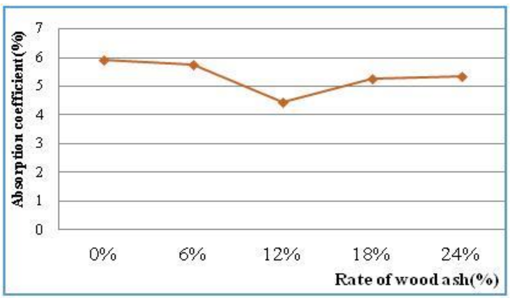

Figure 16. Effect of substitution rate on water absorption variation

4.3.2 Capillary absorption

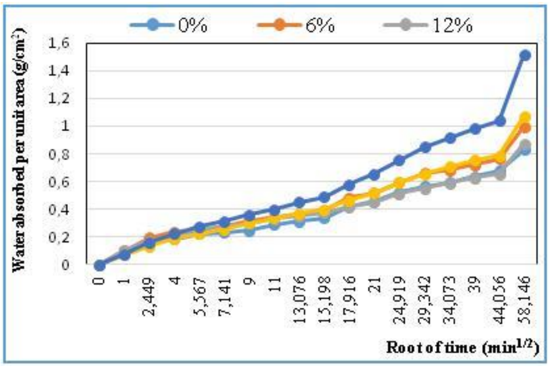

Figure 17. Variation of absorption by capillarity as a function of root of time

The absorption of water by capillarity (Figure 17) increases with time and the substitution rate except for the SCC of 12% of substitution rate which presents a maximum compactness and a variation comparable to that of the control SCC. Wood ash is one of the hygroscopic materials that gives concrete an ability to absorb more water by capillarity [34].

4.3.3 Chlorides penetrations

Figure 18 shows a decrease in chloride ion penetration depth in all wood ash-based SCCs compared to control SCCs, 12% and 18% wood ash SCC blends show the best resistance to corrosion saline solution.

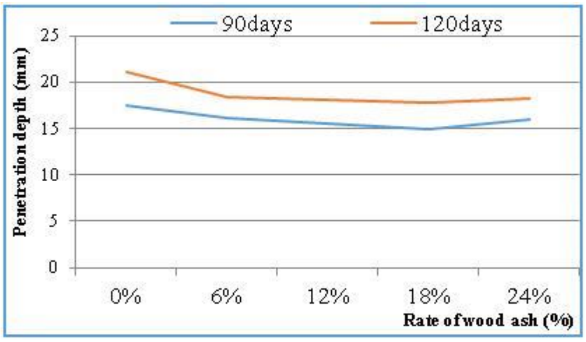

Figure 18. Variation in depth of chloride penetration conting wood ash

At 120 days we find the same trend. The resistance to chloride ions of concrete gives an indirect measure of its permeability and its internal porous structure [2]. Indeed, according to Memon et al. [33], because of their low density and their very fine particles, wood ash increases the volume of the binder matrix and refines the network of pores by filling them and thus makes the SCC microstructure denser and less permeable

4.4 Structural study by XRD and FTIR

From Figure 19 and Figure 20, there was no major difference in the XRD pattern of the control samples and with 24% wood ash.

Calcium carbonate which contributes largely in the resistance is the predominant element in the two samples [17]. The formation of Portlandite in the SCC of 24% of wood ash substitution rate indicates that this material is not inert and participates in the chemical reaction itself [17]. The FTIR results confirm the XRD results.

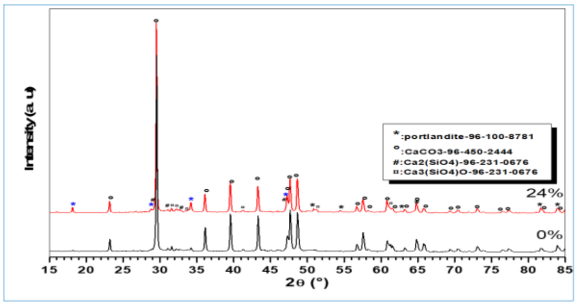

Figure 19. XRD results of hardened concrete specimens

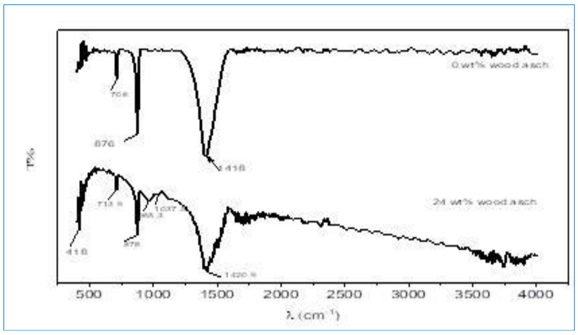

Figure 20. FTIR of SCCs of 0 and 24% wood ash

5. CONCLUSION

From the present research it can be concluded:

- The partial replacement of fine limestone by wood ash causes a decrease in consistency but remains acceptable, the filling capacity increases with the increase in the percentage of ash up to a rate of 18% or the risk of segregation is minimum, satisfactory stability and low risk of static segregation.
- The addition of wood ashes in the SCC formulation leads to a reduction in the flow time to reach a value of 8 seconds, hence a minimum apparent viscosity, which translates into good workability.
- The density and the content of entrained air decreases with the addition of wood ashes to reach a minimum value at 12% of substitution rate, this decrease may be due to the angular shape of the wood ashes which leads to an arrangement in the internal structure of the SCC and makes its compactness maximum at this rate.
- Mixtures based on wood ashes record the best compressive strengths at young age and in the long term, which is due to the presence of Portlandite, which accelerates the formation of the C-S-H gel by a secondary hydration reaction. The best compressive strength is given by the SCC of 18% substitution rate at 28 days of age.
- The behaviour flexural tensile strength is the same as in compression at a young age, and the maximum resistance is given by the SCC of 18% of long-term substitution rate.
- The SCC containing wood ash have higher surface resistances and hardnesses than the control SCCs alone, and significantly influence the homogeneity of the SCC.
- Ultrasonic pulse velocity showed that ash-based SCC are very high strength SCC.

Wood ash has a positive effect on the modulus of elasticity of concrete, which is due to the increase in the adhesiveness of the interfacial transition zone, cement paste/fine aggregates.

- The absorption of water by immersion decreased with the increase in the rate of ash, on the other hand the absorption of water by capillarity increases with time and the rate of substitution except for the SCC of 12% of rate of substitution which presents maximum compactness.

- The depth of chloride ion penetration decreases in all wood ash based SCCs and the 12% and 18% wood ash SCC mixtures show the best resistance to saline solution.

XRD and FTIR analysis indicates that this material is not inert and participates in the chemical hydration reaction.

In a way, the partial replacement of limestone fines by wood ashes positively influences the properties of SCCs and becomes an important solution in the future which allows to reduce the use of these fines.

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