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Posted Date: 17 February 2025

doi: 10.20944/preprints202502.1222.v1

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Article

Performance of Concrete Containing Water-Hyacinth Ash (Wha) as a Cement Replacement: Fresh and Mechanical Properties

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Abstract: Considerable efforts are exerted worldwide to use local and waste materials to avoid stockpiling and conserving the environment. The current research investigates the possibility of using the ash produced from the water-hyacinth plant, which causes enormous environmental problems, as a partial cement replacement. The study revealed that under certain burning and grinding conditions, the water-hyacinth ash (WHA) has amorphous and pozzolanic characteristics. The research presents the fresh and mechanical performances of the WHA in paste, mortar, and concrete mixtures. The experimental evaluation included two WHA burning conditions (in the open air for 60 min and closed oven at 600oC for 30 min), different cement replacement ratios (5%, 10%, 15%) by WHA, and the use of three coarse aggregate types. The results illustrate that the WHA is a pozzolanic material that contributes to strength gain over time. The concrete containing WHA showed better performance than the control made with only Portland cement and comparable behavior to mixtures containing 10% silica fume. Based on the current study, the 10% WHA replacement ratio to cement can be considered optimum. The two WHA types obtained from the two different burning methods yielded a slight difference in performance, and the choice should be optimized based on environmental conservation.

Keywords: Water-hyacinth ash (WHA); Supplementary Cementing Materials; Cement-based Materials; Fresh and Mechanical performance; Silica fume (SF)

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1. Introduction

When producing cement-based materials, not only good mechanical and durability characteristics must be considered, but also environmental friendliness, ecological impact, and socioeconomic benefits must be considered [1,21]. Using alternative supplementary cementitious materials (ASCMs) for partial replacement of cement in concrete would reduce cement production, which is costly, consumes natural resources, and negatively affects environment through CO_2 emissions and increasing greenhouse effect [2]. From economic, technological, and ecological points of view, cement replacement materials have undisputed roles in the future of the construction industry. Small amounts of inert fillers have always been acceptable as cement replacements, but if the fillers have pozzolanic properties, they impart not only technical advantages to the resulting concrete, but also enable larger quantities of cement replacement to be achieved. Many of these mineral admixtures are industrial by-products like silica fume, slag, and fly ash. Other manufactured pozzolans have a vegetable origin like rice-husk ash, rice-straw ash. Extensive research has been carried out in this respect [3–7,22,23]. They dealt with the production and utilization of pozzolanic and cementitious by-products in many countries around the world.

Water hyacinth plants (Figure 1) are native to Latin America but they have been widely spread throughout the world. They were introduced to the USA in the 19th century in the state of Louisiana.

 doi:10.20944/preprints202502.1222.v1

Shortly, thereafter, water hyacinth made their way to the central states of America and other warm parts of the world. Water hyacinth is exceptionally productive, and it multiplies rapidly, it can double its number in two weeks [8]. Mass of freshwater hyacinth planted acre is 153 tones, among which, 27.7% is a dry material. Water hyacinth plants curtail river transports, damage canal walls, increase water evaporation losses, decrease amount of oxygen in water, causes organic pollution in slow moving stream and canals. In 1965, water hyacinth plants covered all watercourses of drains and canals in lower and middle Egypt, so that water level increased in main drainage and came back to branch drainage and to agriculture lands [9]. In 1902, Zarnikhet sodium compound succeeded to destroy the water hyacinth but it was a very harmful compound to humans and animals and was prohibited since 1937. In 1988, carbolic and sulpheric acids were sprayed over the water hyacinth to fire it in USA with less success [10]. In Egypt, the ministry of irrigation and water resources used to collect the plant by dredges and burn it on the adjacent berms of the water canals [10]. This method participates significantly to air pollution. In recent years, the researches have been interested in the nutritional values of water-hyacinth plants for animal feeds. On the other hand, the nature of water hyacinth plants opens other applicable uses as reinforcing agents in paper industry [11]. However, the utilization of water hyacinth plants as filler or reinforcing agents in cement mortar or concretes are still very limited [12,13]. The study carried out by [14] indicated that the dry water hyacinth plants have many heavy metals with significant contents that are summarized in Table 1. The values indicated in the table are average values obtained from the complete dried plants, meaning that the root, stem, and leaves. Under controlled burning and sufficiently ground, the water hyacinth plant can be transformed into ash (WHA) rich in the metals contents that can be used as cement replacement material in concrete. The current research reports on the feasibility of using the WHA as partial replacement of cement in paste, mortar, and concrete mixtures.

Figure 1. Water-hyacinth plant and its spread in watercourses.

Table 1. Heavy metal contents of WHA (ppm) (average analysis of root, stem, and leaves) [14].

Heavy Metals	ppm
Iron	5200
Magnesium	2732
Copper	110
Cadmium	57
Zinc	155
Lead	243
Vanadium	90
Nickel	234
cobalt	44

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2. Research Significance

Currently, there is a critical need for new building materials for the new infrastructures construction and for repair and enhancing the performance of existing structures. The required materials should be highly energy efficient, environmentally friendly, sustainable, affordable, cost effective, and resilient. Using alternative supplementary cementitious materials (ASCMs) would reduce cement production, which consumes natural resources, and negatively affects environment through CO_2 emission and increasing greenhouse effect. Water hyacinth plants curtail river transports, damage canal walls, increase water evaporation losses, decrease amount of oxygen in water, causes organic pollution in slow moving stream and canals. The most common method to overcome the water-hyacinth plants related problems is to mechanically collect the plants from the watercourses, then dry and burn it (turning the fresh plants to an ash), however this method participates significantly to air pollution. The current research provides an ecological solution to consume the waste-water-hyacinth ash (WHA) by using it as a partial cement replacement. The research shows experimentally the efficiency of using the WHA as a partial cement replacement in paste, mortar, and concrete mixtures.

3. Experimental Program

3.1. Testing program

To evaluate the feasibility and effectiveness of using WHA as an ASCM in cementitious mixtures, eight paste, eight mortar, and 24 concrete mixtures were prepared and tested. The main investigated parameters and their ranges are given in Table 2. Ordinary Portland cement (OPC), two types of WHA (burnt in open air and burnt in closed oven at 600˚C for 30 minutes), and silica fume (SF) were considered as binder materials. Three replacement ratios (5%, 10%, 15%) of each the two WHA types, and one replacement ratio by SF (10%) were considered in the investigation. The 10% SF was selected as a reference according to [14]. This generated eight variables including, (1) pure OPC as control mix; (2), (3), (4) with 5%, 10%, 15% WHA burnt in open air which were symbolled by $WHA_{(0)}$5%, $WHA_{(0)}$10%, $WHA_{(0)}$15%, respectively; (5), (6), (7) with 5% , 10%, 15% WHA burnt in closed oven at 600˚C for 30 minutes, which were symbolled by $WHA_{(600)}$5%, $WHA_{(600)}$10%, $WHA_{(600)}$15%, respectively; (8) with 10% SF. In addition to those parameters, three coarse aggregate (CA) types (gravel, dolomite, and basalt) that are locally available in Egypt were also incorporated in the concrete mixtures.

The effect of WHA replacement on the setting time of paste mixtures was evaluated using Vicat apparatus. The pozzolanic activity of the WHA was assessed using a method depending on the variation of electrical conductivity of a solution containing the tested WHA [15,16]. The pozzolanic activity indices were measured also using mortar mixtures incorporating various replacement levels of the WHA at testing ages of 3, 7, and 28 days. The 24 concrete mixtures were tested at the fresh state (slump and unit weight) and at the hardened state by measuring the mechanical properties: cube compressive strength (F_{cu}), indirect tensile-splitting strength (F_{sp}), flexural strength (F_{fl}), modulus of elasticity (E_c), and the stress-strain development.

Table 2. Tested parameters.

Type of replacement	Replacement %	Symbol	Aggregate
Only OPC, served as control	0	Pure cement	The concrete mixtures were designed with three aggregate types: gravel, dolomite, and basalt.
WHA burnt in open air ($WHA_{(0)}$)	5%	$WHA_{(0)}$5%	
	10%	$WHA_{(0)}$10%	
	15%	$WHA_{(0)}$15%	
WHA burnt in oven at 600˚C ($WHA_{(600)}$)	5%	$WHA_{(600)}$5%	
	10%	$WHA_{(600)}$10%	
	15%	$WHA_{(600)}$15%	

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SF	10%	SF 10%

3.2. Materials

An OPC confronting the ASTM Type GU cement was used in all the mixtures. The SF obtained from the free silicon company in Cairo Egypt was used in some of the mixtures with 10% replacement level. It was delivered in a powder form with a light-gray color. The chemical composition and physical properties of cement and SF, as provided by the manufacturer, are given in Table 3.

Table 3. Chemical composition and physical properties of cement, silica fume, and water-hyacinth ash (WHA).

	Constituent	Cement	Silica fume	Water-hyacinth ash (WHA)	
				Burnt in air	Burnt in 600°C
Chemical composition	**SiO_2**	**19.49**	93.00	33.9	34.5
	Ti_2O_3	—	—	0.75	0.78
	Al_2O_3	4.70	0.5	6.77	6.95
	Fe_2O_3	3.28	1.5	5.77	6.02
	SO_3	3.4	0.2	—	—
	MgO	2.40	0.5	5.40	5.93
	CaO	62.8	0.2	10.08	11.46
	Na_2O	0.38	0.5	1.26	1.41
	K_2O	0.95	0.5	9.83	10.98
	H_2O	—	0.6	—	—
	MnO	—	—	0.66	0.73
	P_2O_5	—	—	1.04	1.13
	Cl^-	—	—	3.82	4.02
	SO_4^{--}	—	—	2.37	3.74
	Loss On Ignition (LOI)	2.4	1.5	17.93	11.91
	total	99.8		99.60	99.54
Physical properties	Blaine surface area (m^2/kg)	300	17000	—	—
	Bulk density (kg/m^3)	—	280	—	—
	Specific gravity	3.13	2.20	2.52	2.65
	Color	—	Light gray	Dark gray	Light brown

Three types of CA with maximum-nominal size of 25 mm were incorporated in the mixtures; (a) natural gravel, (b) crushed dolomite with irregular and angular shapes, (c) crushed particles of basalt with gray to black color. Natural siliceous sand was used as fine aggregate (FA). The physical and mechanical properties of the FA and CA are given in Table 4. The grading curves of the combined aggregates were in good compliance with the limits of the British Standard code requirements.

Table 4. Physical and mechanical properties of sand and coarse aggregates.

Property	Fine aggregate (sand) (FA)	Coarse aggregates (CA)		
		Gravel	Dolomite	Basalt
Specific gravity (SSD)	2.58	2.52	2.78	2.85
Volume weight (t/m^3)	1.710	1.630	1.615	1.682
Void ratio (%)	33.72	35.2	41.9	41.0
Aggregate crushing value (%)	—	15	19	12
Fineness modulus	2.71	7.55	7.45	7.60
Clay, silt, and fine dust (% by weight)	2.13	—	—	—
Chloride (% by weight)	0.031	0.027	0.032	0.023
Sulfate (% by weight)	—	0.130	0.190	0.160

The water hyacinth plants collected from the river Nile at Delta Barrages area in Egypt were used to obtain the WHA used in the present investigation. The effect of burning process (temperature and condition) on the properties of the resulting ash was investigated, because the increase in the

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burning temperature makes the ash more reactive via breaking the crystalline structure (if any). The process for producing the WHA can be summarized as follows:

1. The water hyacinth plants were harvested from water bodies (initially contains about 95% water) and laid to dry up in open air for 2-3 weeks at a temperature of about 35-40˚C and a humidity of less than 50% (Figure 2a, b). The dry plants had less than 10% water and can be self-ignited and make a fire.
2. The dry plants were burnt (by making a fire) in different conditions either burning in open air for 60 minutes (referred to as $WHA_{(0)}$) or in a closed oven at 600˚C for 30 min (referred to as $WHA_{(600)}$).
3. The resultant ashes were cooled down, then stored in a dry condition.
4. The ashes were ground using Los–Angeles machine (with 1500 rpm), then the fine ashes passed the # 200 standard sieve were collected. The $WHA_{(0)}$ is shown in Figure 2c, where the $WHA_{(600)}$ is presented in Figure 2d.

(a) Fresh water hyacinth plants

(b) Water hyacinth plants after air drying

(c) Burnt in open air water-hyacinth ash

(d) Burnt-in-oven at 600ºC water-hyacinth ash

Figure 2. Fresh and dried water hyacinth plants, and water-hyacinth ashes (WHA).

The physical and chemical characterization of the two WHA types were measured and the results are described in Table 3. The elements expressing the potential of pozzolanic activity (SiO_2, Al_2O_3, and Fe_2O_3) represent approximately 50% of the ash. This value corresponds to that found in some of fly ash types [16]. The large loss on ignition (LOI) values indicate existing of high quantity of organic materials in the resultant WHA. The percentages of WHA mass to the original dry plants that can be obtained from the open-air burning was found slightly greater (27.65%) than that obtained from the oven burning condition (25.85%).

After grinding process, laser-diffraction analysis was carried out on the WHA to determine the particle-size distribution (PSD), and the resultant PSDs are presented in Figure 3. The results indicate that the $WHA_{(0)}$ is coarser than the $WHA_{(600)}$. The respective particle size ranges from 1 to 125 µm for the $WHA_{(0)}$ with mean-particle diameters (d_{50}) of 23 µm, and ranges from 1 to 62 µm for the $WHA_{(600)}$ with a d_{50} of 12 µm.

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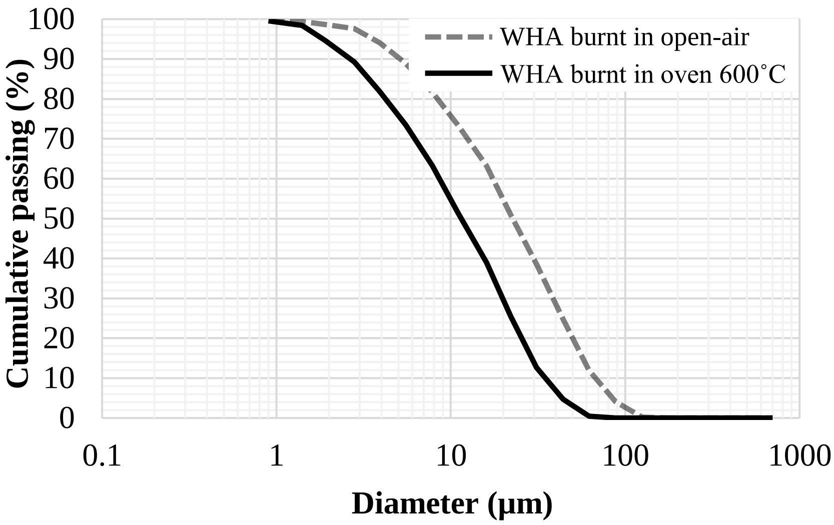
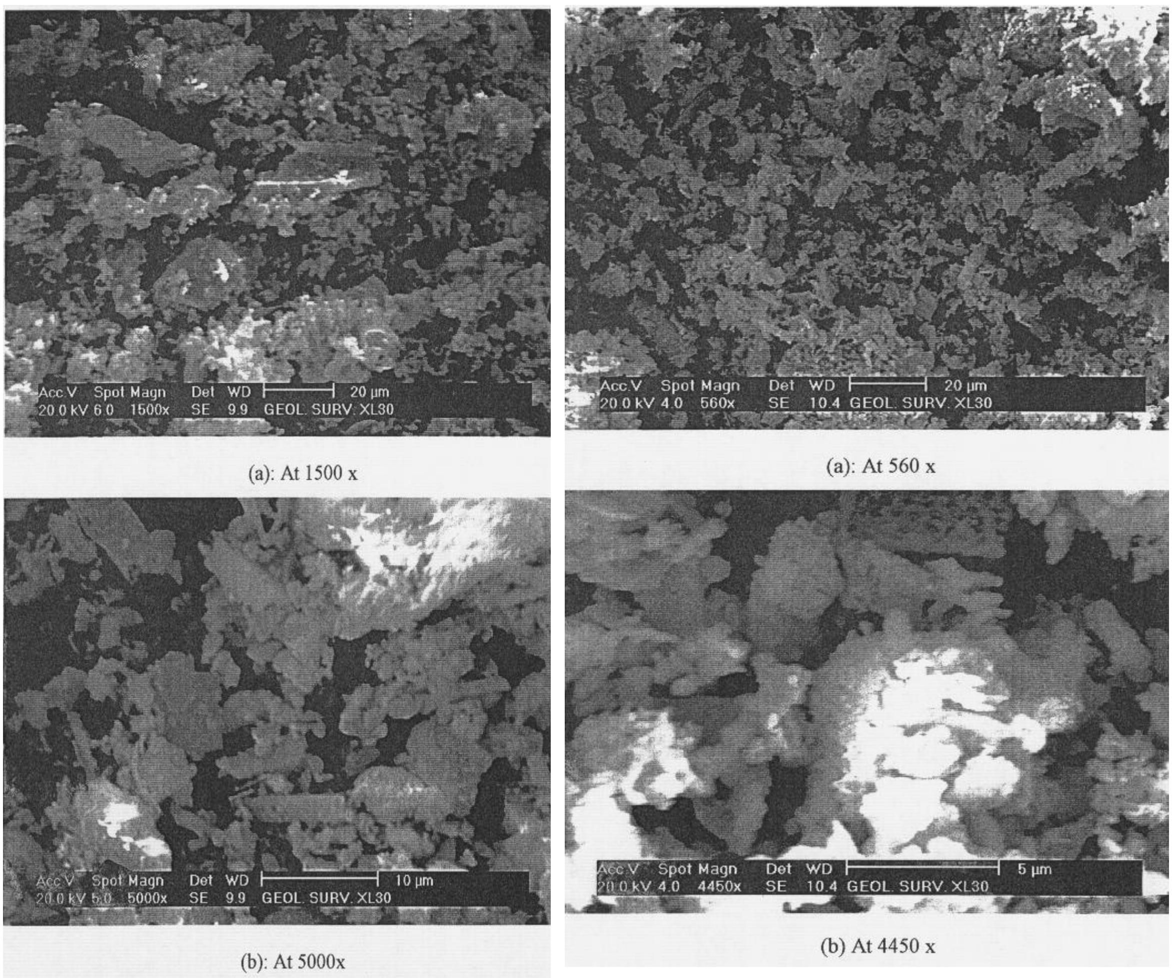


Figure 3. Particle-size distribution of water-hyacinth ash (WHA) burnt in open air and closed oven at 600 ºC.

The scanning-electron microscope (SEM) photography using SEM model Philips XL30 attached with EDX unit was carried out on the WHA powders, and the results are shown in Figure 4. The WHA is porous and mainly contained angular particles of irregular shape and rough textures, where there are few spherical particles with smooth surfaces similar to the OPC particles [18], as illustrated in the micrograph Figure 4.



(A) WHA burnt in open air (B) WHA burnt at 950ºC

Figure 4. SEM micrograph of WHA particles [18].

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3.3. Mixture proportions, mixing sequence, samples preparation, and curing conditions

All the materials used to make paste, mortar, or concrete mixtures were kept at 23 °C for 24 hours prior mixing.

Paste mixtures – The water content for making the paste mixtures was determined based on the necessary water content for obtaining the normal consistency level. We started with the water content for obtaining the normal consistency level of the paste mixture containing only OPC (based on the manufacture data sheet), and then kept the same water-to-cementitious materials ratio (*w/cm*) for the other paste mixtures containing blended cement and WHA or SF.

Mortar mixtures – The mixture proportions for the mortars were cement+replacement : sand : water of 1 : 3 : 0.4. The batching of mortar consisted of homogenizing cement and sand with a trowel for 1.0 minute, and then the water was added and mixed for additional 3.0 to 4.0 minutes. Immediately after mixing, the mortar is filled into a 7.06-cm cube molds of a 50-cm^2 surface area. The molds were compacted using vibrating table according to the Egyptian Standard Specification No. 2421. Mortar samples were moist cured at 23ºC until the day of testing at 3, 7, and 28 days.

Concrete mixtures – All concrete mixtures were designed based on the dry condition of aggregates using the absolute volume method. The cementitious materials were; 300 kg/m^3 of OPC, OPC blended with 5%, 10%, 15% $WHA_{(0)}$ (by weight), OPC blended with 5%, 10%, 15% $WHA_{(600)}$ (by weight), and OPC blended with 10% SF (by weight). The *w/cm* was set at 0.50, without any superplasticizer addition. The ratio between the CA and FA was 2.0. The detailed concrete mix designs are given in Table 5.

Table 5. Concrete mix design.

Group	Mix no.	Mix proportions (kg/m^3)							*w/cm*	CA/FA	Rep/C
		C	W	FA	CA	Replacement (Rep)					
						$WHA_{(0)}$	$WHA_{(600)}$	SF			
Gravel concrete	OPC	300	150	638	1276	—	—	—	0.5	2	—
	$WHA_{(0)}$5%	285	150	637	1274	15	—	—	0.5	2	0.05
	$WHA_{(0)}$10%	270	150	636	1272	30	—	—	0.5	2	0.10
	$WHA_{(0)}$15%	255	150	635	1270	45	—	—	0.5	2	0.15
	$WHA_{(600)}$5%	285	150	637	1274	—	15	—	0.5	2	0.05
	$WHA_{(600)}$10%	270	150	637	1273	—	30	—	0.5	2	0.10
	$WHA_{(600)}$15%	255	150	635	1271	—	45	—	0.5	2	0.15
	SF 10%	270	150	635	1269	—	—	30	0.5	2	0.10
Dolomite concrete	OPC	300	150	681	1362	—	—	—	0.5	2	—
	$WHA_{(0)}$5%	285	150	680	1360	15	—	—	0.5	2	0.05
	$WHA_{(0)}$10%	270	150	679	1358	30	—	—	0.5	2	0.10
	$WHA_{(0)}$15%	255	150	678	1356	45	—	—	0.5	2	0.15
	$WHA_{(600)}$5%	285	150	680	1360	—	15	—	0.5	2	0.05
	$WHA_{(600)}$10%	270	150	679	1359	—	30	—	0.5	2	0.10
	$WHA_{(600)}$15%	255	150	679	1357	—	45	—	0.5	2	0.15
	SF 10%	270	150	677	1355	—	—	30	0.5	2	0.10
Basalt concrete	OPC	300	150	692	1385	—	—	—	0.5	2	—
	$WHA_{(0)}$5%	285	150	691	1382	15	—	—	0.5	2	0.05
	$WHA_{(0)}$10%	270	150	690	1380	30	—	—	0.5	2	0.10
	$WHA_{(0)}$15%	255	150	689	1378	45	—	—	0.5	2	0.15
	$WHA_{(600)}$5%	285	150	692	1383	—	15	—	0.5	2	0.05
	$WHA_{(600)}$10%	270	150	691	1381	—	30	—	0.5	2	0.10
	$WHA_{(600)}$15%	255	150	690	1380	—	45	—	0.5	2	0.15
	SF 10%	270	150	689	1377	—	—	30	0.5	2	0.10

In order to obtain a uniform concrete mix, mixing was performed using an open pan mixer of 50-L capacity at 20-rpm speed. The CA and FA were first charged in a mixer and homogenized for 1.0 minute, then cement (mixed with replacement materials; WHA or SF) was added and mixed for another 1.0 minute. The mixing water was finally added followed by a final mixing period of 3.0 minutes. At the end of mixing, the slump and unit weight for each concrete were measured.

Cubes specimens measuring 100 x 100 x 100 mm were prepared for measuring the F_{cu} (ASTM C39/C39M-20). Cylindrical specimens measuring 100 x 200 mm were prepared for measuring the F_{sp} (ASTM C496/C496M-17), while other cylinders measuring 150 x 300 mm were prepared for determining the stress–strain relationship, cylindrical compressive strength (F_{cy}) (ASTM C39/C39M-20), and E_c (ASTM C469/C469M-14). Prisms measuring 100 x 100 x 500 mm were prepared for measuring the F_{fl} using four-point loading system (ASTM C78/C78M-18). Schematic diagrams for these tests are illustrated in Figure 5. For each mixture and for each testing age, the average of three (3) samples that produce relative errors of less than 7% according to corresponding ASTM standards were only considered.

The concrete was placed in molds in layers of 50 mm in thickness and subjected to 30 blows using a standard compacting rod. The cast molds were then placed on a vibrating table for 30 seconds before surface finishing. The specimens were kept in the molds at a temperature of about 23°C and a relative humidity (RH) of 50% for 24 hours before demolding and storing in lime-water path at 23°C until the date of testing or 28 days at maximum. After 28 days, the specimens were removed from the water and kept in the laboratory atmosphere (a temperature of about 23°C and a RH of 50%). The results are the average of three samples.

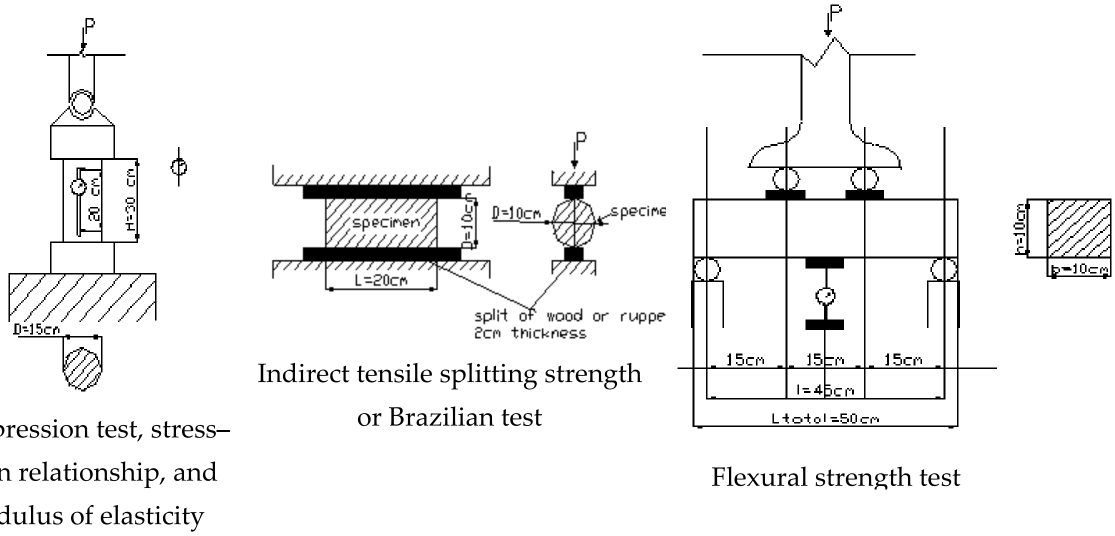

Figure 5. Schematic diagrams for compressive, indirect-tensile, and flexural strength tests and modulus of elasticity.

4. Results and Discussions

4.1. Paste results

The evaluation of the pozzolanic activity of the WHA was made using the variation of electrical conductivity of a solution containing the tested WHA [15,17]. The electric conductivity of 5% $Ca(OH)_2$ solution (200 ml) at 40°C was measured, and then 5 gm of the WHA was added and stirred in the solution and the electrical conductivity was measured again after 2.0 minutes. The difference in the electrical conductivity measurements represents the potential of pozzolanic activity of the WHA. The variations in the electrical conductivity determined for the $WHA_{(0)}$ (burnt in open air) and $WHA_{(600)}$ (burnt in closed oven at 600°C) according to [15,17] were 7.10 and 5.28 ms/cm, respectively. These values were significantly greater than the values set by the test as a limit for obtaining a material with a good pozzolanic activity characteristics (1.2 ms/cm).

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The chemical analysis of the WHA shows existence of a higher Al_2O_3 amount than the cement (6.77% for the $WHA_{(0)}$ and 6.95% for the $WHA_{(600)}$ versus 4.70% for the OPC), which has a potential effect on setting time. Therefore, the effect of the ash on the setting time was evaluated using paste mixtures incorporating all the WHA/cement and SF/cement combinations indicated in Table 2 and made with the *w/cm* that gives the normal consistency level. The Vicat apparatus was used to measure the initial and final setting times, and the results are presented in Figure 6. shows the initial and final setting times determined using the Vicat needle test versus. The results of the different replacement ratios from the two types of WHA are compared to the 10% SF and the control mixture (with only OPC) in the figure. The results indicate that the setting times measured for the two WHA types obtained from the two different burning conditions are almost similar, this is due to the very close Al_2O_3 contents (6.77% vs. 6.95%). As expected, the mixtures incorporating WHA exhibited shorter setting times than the control, with more tendency to short setting times at the increased replacement ratios. This was due to the higher Al_2O_3 content in the WHA compared to the OPC. The 10% WHA (either under the different burning conditions) showed slight longer setting times than the mixture containing 10% SF due to the finer particles of the SF.

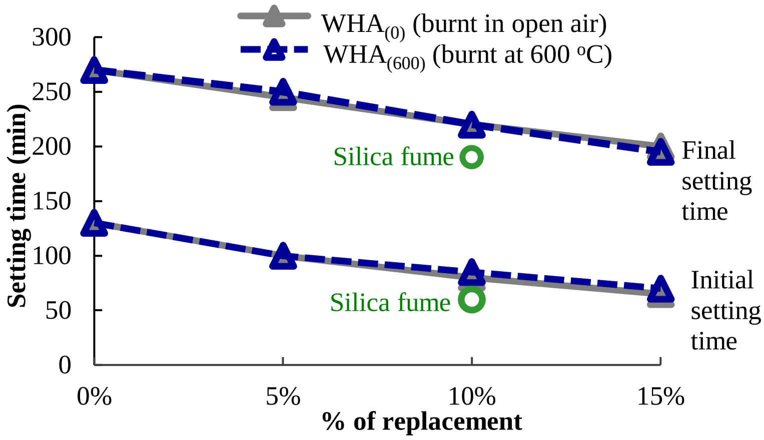

Figure 6. Initial and final setting times for paste mixtures made with different types and contents of water-hyacinth ash (WHA) in comparison to control and 10% silica fume.

4.2. Mortar results

Figure 7 shows the effect of content and type of WHA on the mortar compressive strength at testing ages of 3, 7, and 28 days. For $WHA_{(600)}$, the compressive strength increased with increase in the replacement ratio and reached a peak between 5% to 10% replacement ratio, then strength reduction was observed even below the control value at replacement beyond the 10% ratio. This trend was similar at all ages. For the $WHA_{(0)}$, there was an increase in strength with the increase of replacement ratio. However, this increase was maximum at 7 days. The percentages of maximum increase in strength for 3, 7, and 28 days were 47%, 31%, and 18% for the $WHA_{(0)}$, and were 61%, 42%, and 25% for $WHA_{(600)}$, respectively.

By using 10% SF, the results obtained were 43%, 34%, and 18% higher than the control mix at 3, 7, and 28 days, respectively. The 3-, 7-, and 28-day strength results obtained from using 10% WHA can be comparable to those obtained from using 10% SF, with a minor decrease. This was mainly due to the higher fineness of the SF compared to the WHA.

The normalization of the compressive strength of the mortar mixtures made with the WHA or SF relative to that made only with OPC give the strength activity index (SAI). The ASTM C618-19 standard recognizes that the material resulting in SAI value either at 7 or 28 days higher than 0.75 is a good pozzolanic material. The SAI results shown in Table 6, indicate that the cement replacement by any of the two WHA types or SF at all replacement levels were greater than 0.75 except for the 15% $WHA_{(600)}$, which exhibited 0.68 and 0.60 at 7 and 28 days, respectively. The SAI values for the

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evaluated mortars indicated in Table 6 confirm also the accelerating effect of the WHA in the early age (7 days) compared to the 28-day results.

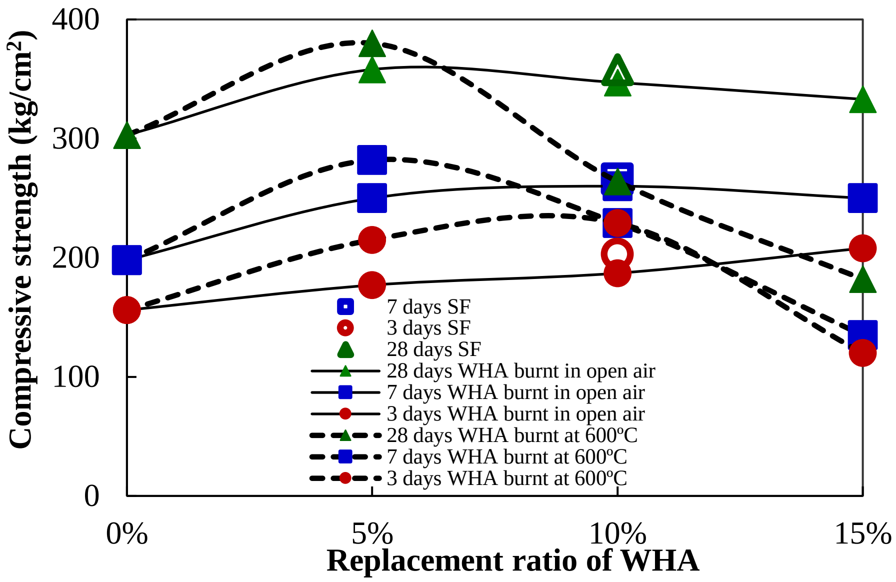

Figure 7. Compressive strength (after 3, 7, and 28 days of curing) of mortar mixtures versus replacement ratio.

Table 6. Strength activity index (SAI) of tested mortars.

Materials	Replacement ratio	Pozzolanic activity index	
		7 days	28 days
Pure OPC	0%	1.00	1.00
WHA burnt in open air, $WHA_{(0)}$	5%	1.26	1.18
	10%	1.31	1.15
	15%	1.26	1.10
WHA burnt in oven at 600ºC, $WHA_{(600)}$	5%	1.42	1.25
	10%	1.16	0.87
	15%	0.68	0.60
S.F.	10%	1.34	1.18

4.3. Fresh concrete results

4.3.1. Workability

The workability of the concrete mixtures was measured directly using the Abraham cone at the end of mixing, and the results are shown in Figure 8. When WHA or SF was introduced into the concrete, the workability decreased as part of cement was replaced with WHA or SF. The results showed also more slump loss with the increase in the replacement ratio by the WHA. The workability of concrete mixture is enhanced by decreasing the friction between aggregate particles, which can be achieved by increasing the paste content of the mixture. However, when the paste volume is constant, the characteristics of the particles of the cementitious materials play a significant role as in the current case. The WHA of the porous, angular, irregular shape, and rough textures particles required higher water content compared to the cement particles, given that the WHA and cement had approximately similar fineness. The higher percentage of the Al_2O_3 in the WHA compared to cement can also interpret the slump loss for the mixtures containing WHA. However, introducing the SF with large specific surface area compared to the cement particles required also higher water content to lubricate the surface area of the particle. While maintaining the same water contents for all concrete mixtures, this affected the final workability. There was a probability of workability increase with increasing

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WHA content due to the cement dilution, which tends to reduce the formation of cement hydration products in the first few minutes of mixing. Therefore, there were insufficient products to bridge various particles together. It is worth noting that the WHA replacement of cement was by weight. As the specific gravity of WHA was lower than that of cement, the solid particles-to-water ratio, by volume, was higher than in case of cement and WHA blends compared to only OPC. This increased the friction between the solids in the paste in the case of the WHA/OPC blend, thereby resulting in a slight improvement in workability. This positive effect of cement dilution on workability was less effective compared to the rough and porous WHA particles. The higher WHA content ended up with bad workability.

Relative to the control mixture, the slump losses for the concretes containing $WHA_{(600)}$ (burnt in controlled media at 600˚C) were slightly higher than those of the concretes containing $WHA_{(0)}$ (burnt in open air), due to the finer particles of the former compared to the latter ashes (d_{50} = 12 vs. 23 µm, respectively). In addition, the slump of gravel concretes was higher than that of basalt concretes, then the dolomite concretes, which ranked the third. This was related to the surface texture and shape of the aggregates. The natural gravel was rounded and solid surface texture, crushed dolomite had with irregular and angular shapes with more porosity, and the basalt was crushed with non-porous particles.

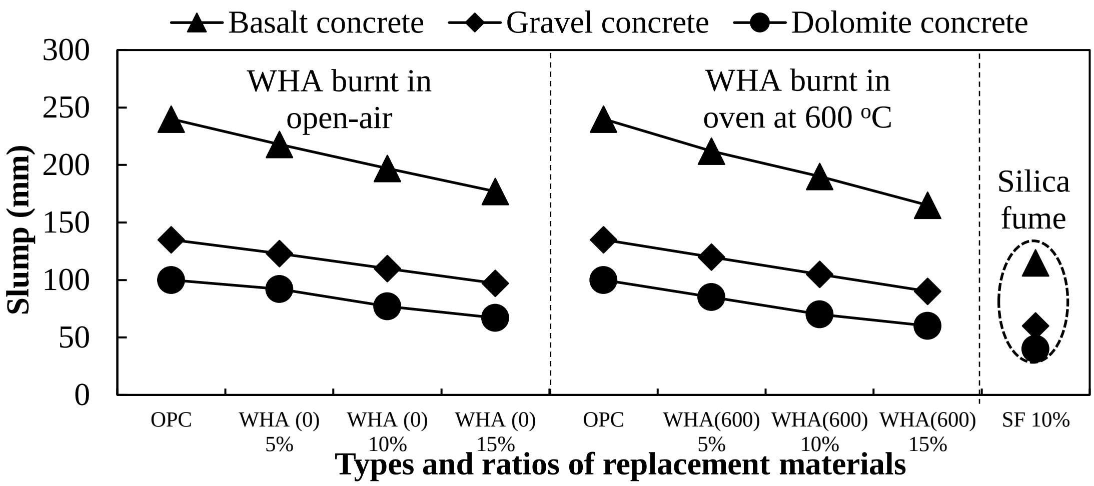

Figure 8. Slump consistencies of investigated concrete mixtures.

4.3.2. Unit weight

The unit weight results of the evaluated concrete mixtures are given in Table 7. The control concrete mixtures gave the largest values: the gravel, dolomite, and basalt concretes resulted in 2364 2493, and 2527 kg/m³ unit weight values, respectively, while the WHA concretes showed lower values than the control. The unit weight of concrete changes normally due to the change in the mix proportions or the properties of the ingredients used. In current results, the partial replacement of OPC by WHA of lower density of the WHA yielded lower unit weight values. In fact, the density values of the $WHA_{(600)}$ concretes were lower than the control but higher than those containing the $WHA_{(0)}$ or SF, because the densities of the OPC, $WHA_{(600)}$, $WHA_{(0)}$, and SF were 3.13, 2.65, 2.52, and 2.2, respectively.

Table 7. Fresh concrete unit weight.

Concrete mixture	Unit weight (kg/m³)		
	Gravel	Dolomite	Basalt
OPC	2364	2493	2527
$WHA_{(0)}$5%	2361	2490	2524
$WHA_{(0)}$10%	2358	2487	2521

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$WHA_{(0)}$15%	2355	2483	2517
$WHA_{(600)}$5%	2362	2490	2525
$WHA_{(600)}$10%	2359	2488	2522
$WHA_{(600)}$15%	2357	2486	2520
SF 10%	2354	2482	2516

4.4. Hardened concrete results

The results of the various mechanical properties of WHA concretes including compressive, tensile, and flexural strengths as well as the static Young's modulus in compression are discussed in the following sections.

4.4.1. Cubes compressive strength (F_{cu})

The results of the F_{cu} after curing periods of 3, 7, 28, 90, 180 days are shown in Figure 9 for three types of coarse aggregates; gravel, dolomite, and basalt. Each reported result is an average of three specimens.

The F_{cu} increases with age but the rate of strength development was higher in the early age. Most of the strength development took place before the 90 days, with limited strength development beyond that. This indicates that the effect of the WHA on strength gain is approximately similar to the rapid hardening cement.

The F_{cu} for the concrete containing 5% and 10% WHA was higher than that of the reference. The pozzolanic reactivity and the filling effect of the WHA can explain this increase. On the other hand, the strength of the concrete containing 15% WHA was lower than that of the reference. This might be due to the fact that the quantity of WHA in the mix may be higher than the required to react with the liberated calcium hydroxide resulted from cement hydration, thus leading to excess silica leached out and causing a deficiency in strength as it replaces part of the cementitious material but does not contribute to strength. This was the case for both burning conditions; $WHA_{(0)}$ and $WHA_{(600)}$. This trend was same at all testing ages. The concrete made with 5% WHA in some cases were found similar or greater than the concrete containing 10% SF. The F_{cu} results for the WHA and SF concretes are matching the strength activity indices carried out on mortar (Table 5). These findings are similar to the results obtained in [19,20].

The effect of burning method had no clear effect on the F_{cu}. The F_{cu} of the $WHA_{(0)}$ concretes were similar to those made with $WHA_{(600)}$ with little variations. This can be due to the temperature in the open-air burning of the WHA was around the 600°C used in the controlled oven-burning.

It can also be observed that the F_{cu} results for the basalt concretes were greater than dolomite concretes, which in their turn were greater than the gravel concretes. This is referred to the relative crushing strengths and the surface texture of different aggregates.

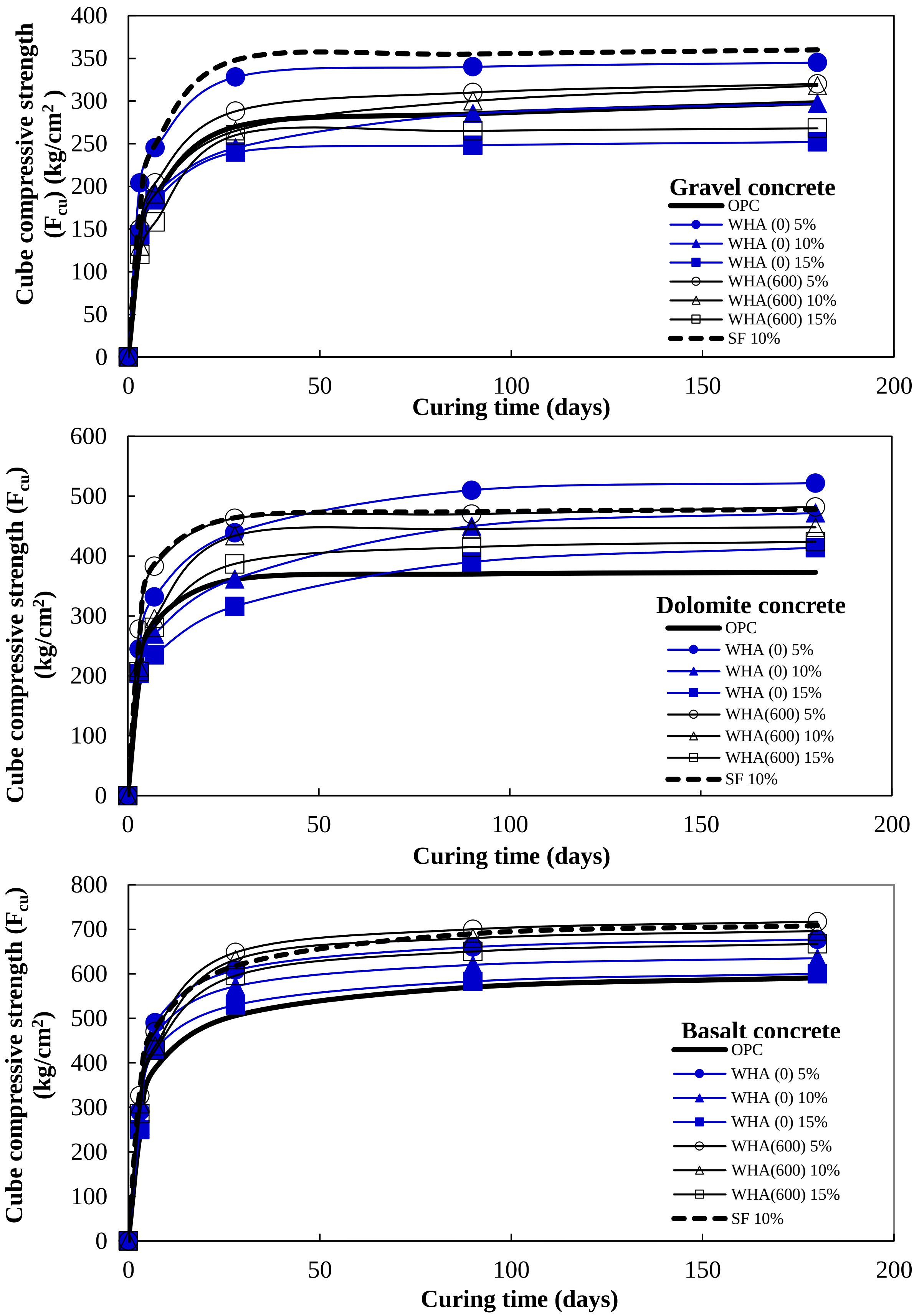

Figure 9. Development of cube compressive strength (F_{cu}) for the investigated concrete mixtures.

4.4.2. Splitting-tensile strength (F_{sp})

Normally, plain concrete is not strong enough to resist tension loads, leading to cracking when subjected to shrinkage or any tensile stresses. So, improving the tensile strength of concrete by using

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alternative supplementary cementitious materials such as WHA is of importance for increasing the potential to crack resistance. The 28-day F_{sp} results for the 24 concrete mixtures listed in Table 5, are illustrated in Figure 10. Each reported F_{sp} result is an average of three specimens.

The F_{sp} for the concrete mixtures made with WHA at all replacement ratios were greater than the control concrete (with only cement). The maximum increase in the F_{sp} relative to the control were reported at 5% WHA and reached about 50%, such as in the case of gravel concrete with $WHA_{(0)}$5% and basalt concrete with $WHA_{(600)}$5%. These values were higher than those for the concrete mixtures containing 10% SF (the increase ranged between 39% and 44%). These findings are similar to the results obtained by other researchers [19]. However, incorporating higher percentage of WHA than 5% resulted in reduction in the F_{sp}, but in all cases, it was greater than the reference. The increase in the F_{sp} with 15% WHA replacement was limited to less than 6% compared to the reference. As explained earlier in the compressive strength, this tensile strength gain can be due to the pozzolanic reactivity and the filling effect when incorporating WHA at 5% replacement, which becomes less effective at higher replacement ratios.

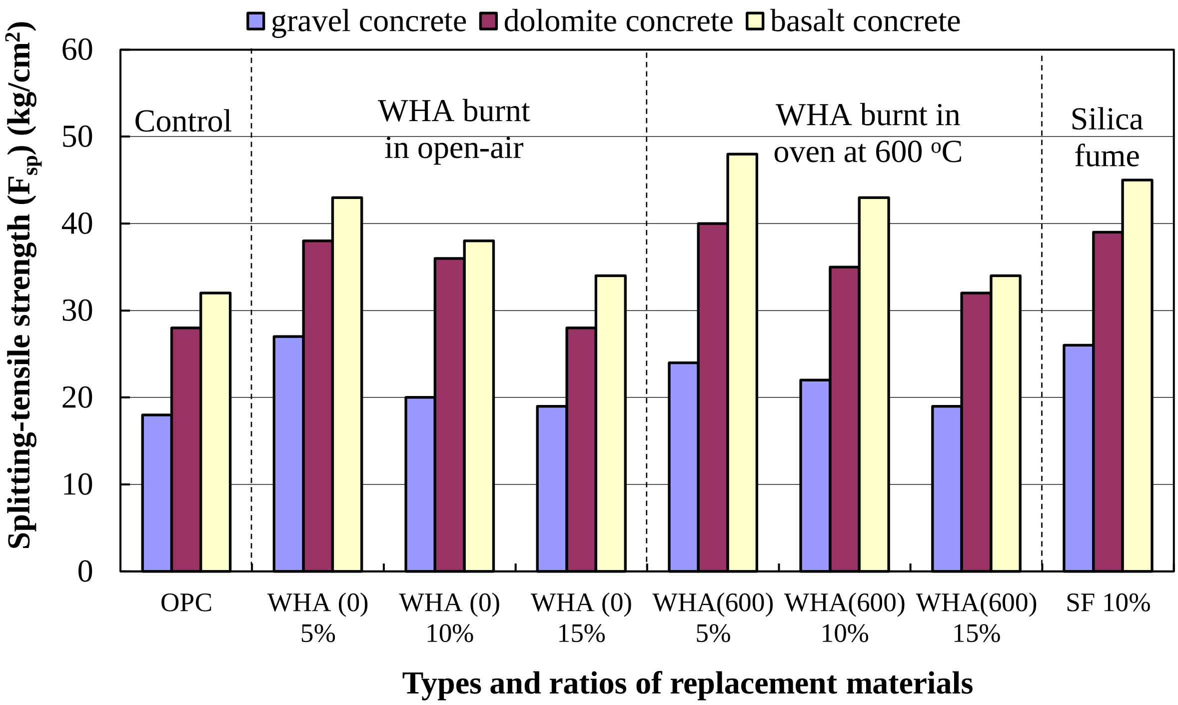

Figure 10. Splitting-tensile strength (F_{sp}) (after 28 days of curing) for investigated concrete mixtures.

4.4.3. Flexural strength (F_{fl})

The 28-day F_{fl} results carried out on the 24 concrete mixtures listed in Table 5 are illustrated in Figure 11. Each reported result is as an average of three prisms. Data from the F_{fl} tests showed approximately similar trend as that of the F_{sp}. In general, the F_{fl} results showed that all concrete mixtures (with different coarse aggregate types) made with 5% and 10% WHA replacement ratios were higher than control; however, the mixtures with 15% WHA were less. In addition, the F_{fl} when using $WHA_{(600)}$ was higher compared to the $WHA_{(0)}$. The results can confirm that the 5% WHA replacement ratio was the best resulting in the maximum F_{fl}, which in its turn was a bit less than the concretes made with 10%SF. In addition to the pozzolanic reactivity and the filling capacity, the enhancement in the F_{fl} when using the WHA can be referred to the enhancement in the transition zones between the cement paste and aggregates.

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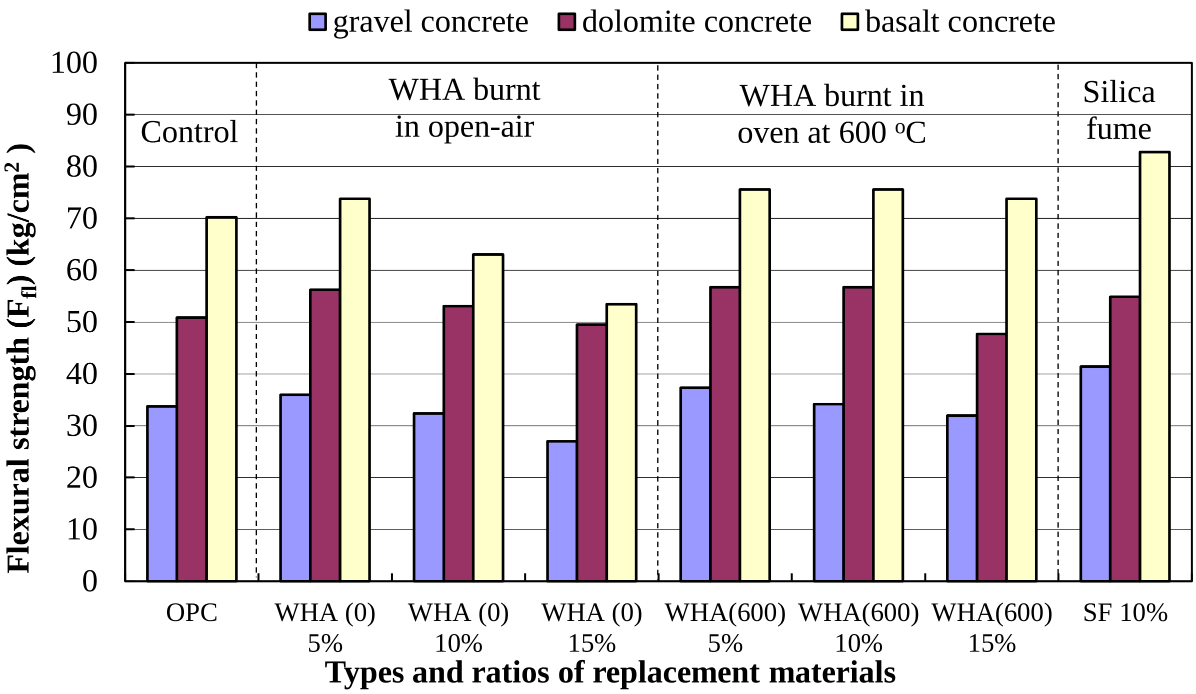

Figure 11. Flexural strength (F_{fl}) (after 28 days of curing) for investigated concrete mixtures.

4.4.4. Stress–strain relationship and modulus of elasticity (E_c)

For each cylinder, the stress–strain in compression was measured using a 20-cm mechanical strain gauge until the maximum stress (strength) is reached. Figure 12 shows comparisons between the stress–strain relationships for the gravel, dolomite, and basalt concretes using cylinders specimens. As expected, the concretes made with basalt showed the maximum load capacity, followed by those made with dolomite, then by the gravel aggregates, governed by the relative hardness of the various aggregate types.

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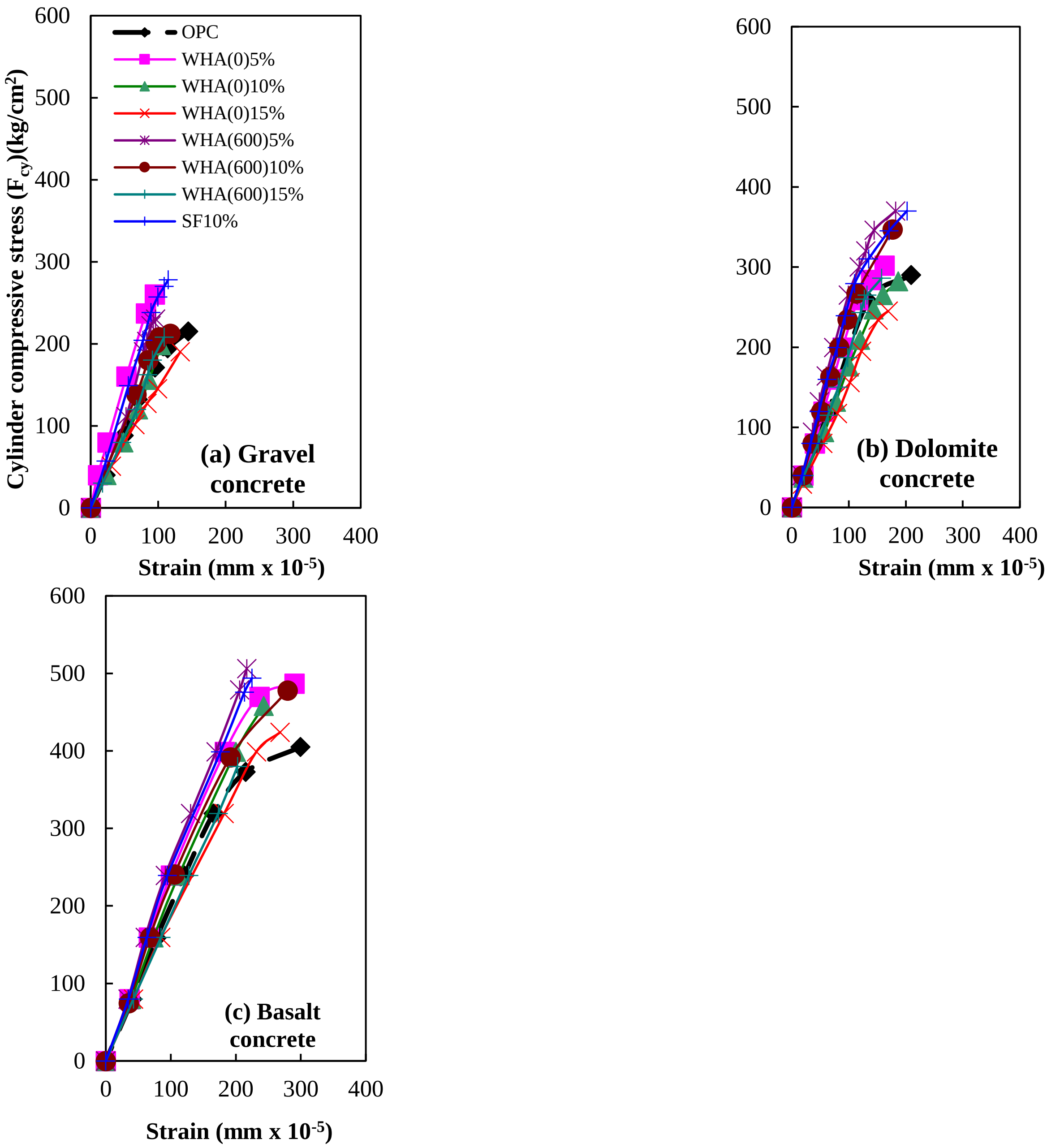

Figure 12. Stress-strain curves after 28 days of curing for the investigated concrete mixtures.

Concrete as a structural material is elastic to a certain extent. The E_c was calculated as the initial tangent of the stress-strain curve during this elastic region. The E_c values for the concretes under investigation are illustrated in Figure 13. The dolomite concretes with all replacement materials and ratios were found to be greater than the reference, proofing the satisfactory adherence between the cement paste and dolomite. The 5% WHA replacement ratio was again proved to be the most effective replacement ratio in enhancing the E_c, as the case in enhancing the other strengths.

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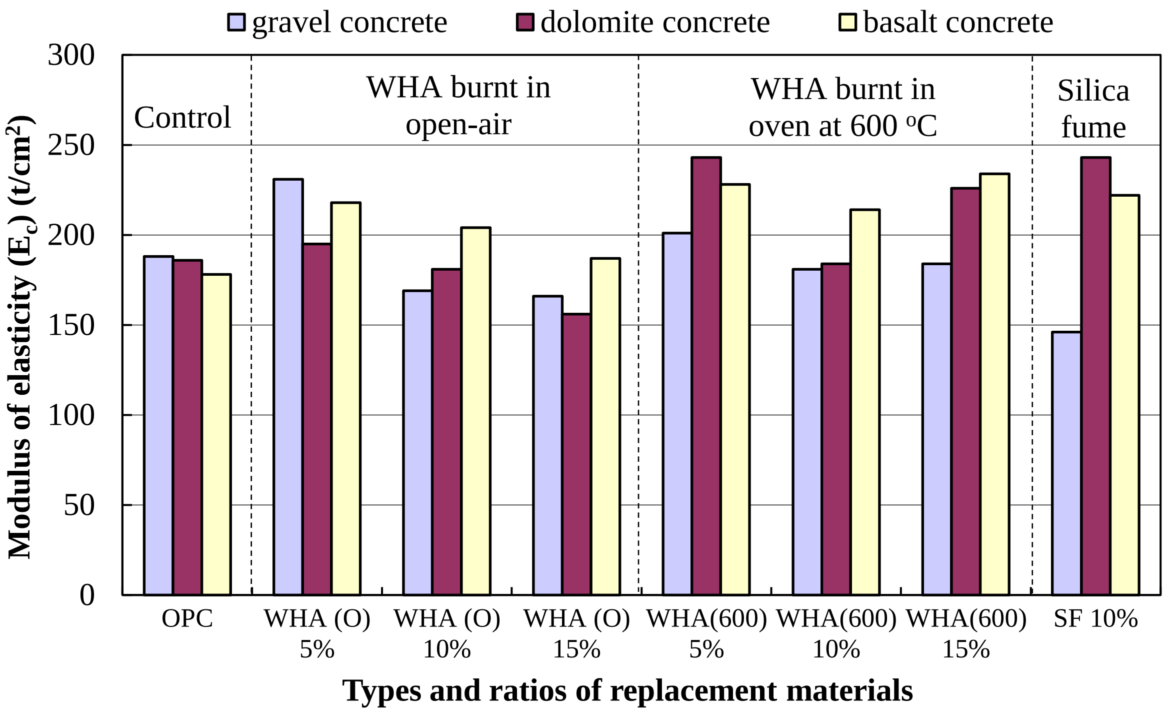

Figure 13. Modulus of elasticity (E_c) (after 28 days of curing) for investigated concrete mixtures.

4.4.5. Relationship between cylindrical and cubic compressive strength

The maximum cylindrical compressive strength (F_{cy}), obtained when measuring the stress–strain curves, were measured and illustrated in Figure 14. The F_{cy} was measured at the age of 28 days. These results are matching those reported in Figure 9.

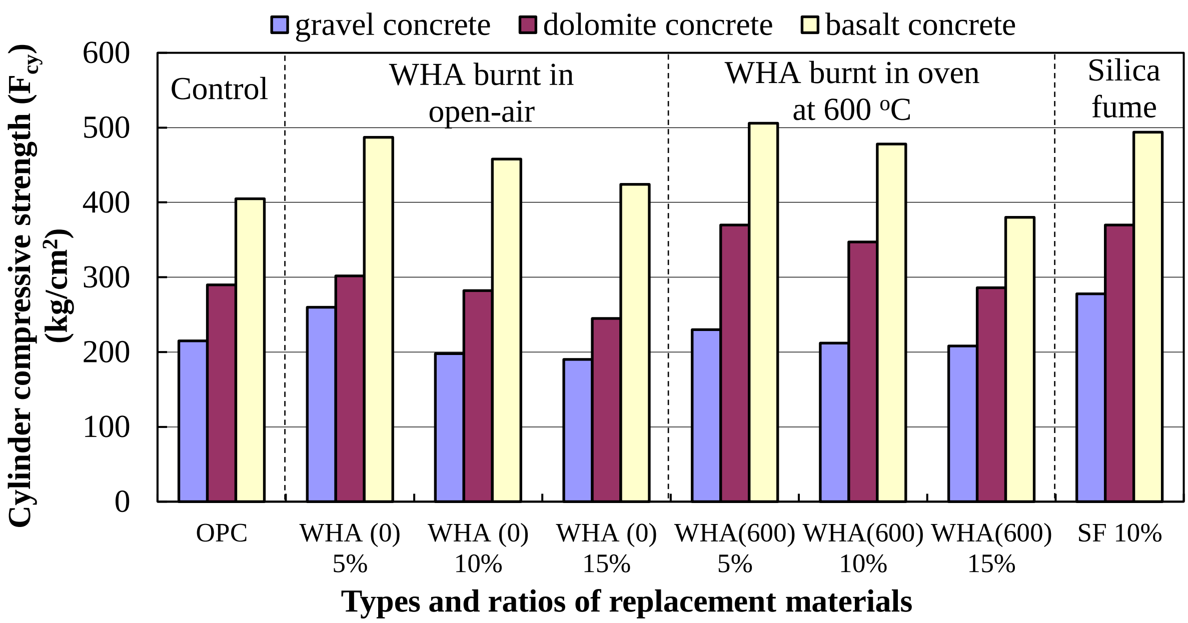

Figure 14. Cylinder compressive strength (after 28 days of curing) for investigated concrete mixtures.

The 28-day F_{cy} were correlated to the 28-day F_{cu} from Figure 9, as given in Figure 15. This correlation reveals a linear relationship with 30% increase in the F_{cu} compared to the F_{cy}.

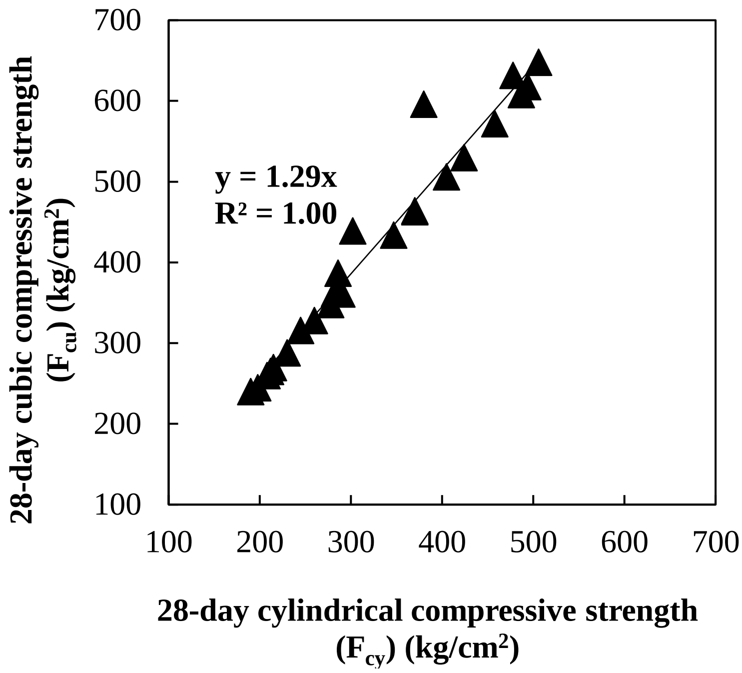

Figure 15. Relationship between 28-day compressive strength carried out using cubes and cylinders for investigated concrete mixtures.

5. Conclusions

The research concerns using water hyacinth (W.H.), which obstructs navigation and absorbs huge quantities of water, as a partial replacement of cement. Based on the experimental program achieved, it can be concluded that:

1. Using water hyacinth plants after burning as a cement replacement material in concrete mixes participates in keeping the environment clean. Otherwise, these plants can hinder the watercourse navigation, absorb large quantiles of fresh water, and increase the amount of waste materials on rivers banks.
2. Considering the water hyacinth as a waste material, its valorization in concrete as cement replacement could be considered as cost saving of cement production.
3. In manufacturing the water hyacinth ash (WHA), burning in closed ovens produces ash with similar composition to that burnt in open air, but with less effect on the environment.
4. The electric conductivity on a 5% $Ca(OH)_2$ solution carried out on WHA burned in the two conditions (air and in closed oven at 600°C) proved a good pozzolanic activity of these ashes.
5. The strength activity index (SAI) determined for mortar made with 5% and 10% WHA replacement ratio shows higher values than 0.75 stipulated by the ASTM C618-19 to consider the material as a pozzolanic.
6. The WHA is an accelerating additive that decreases the initial and final setting times by up to 50% due to the existence of higher Al_2O_3 content.
7. At the same w/cm ratio, more slump loss can be expected when incorporating higher WHA replacement ratios in concrete due to the porous, angular, irregular shape, and rough textures of the WHA particles that requires higher water content compared to the cement particle, given that the investigated WHA and cement have approximately similar fineness.
8. Using 5% WHA as cement replacement was found to be the best, leading to a distinguished increase in concrete strength compared to the control due to the pozzolanic activity, filling capacity, and enhancing the transition zones between cement paste and aggregate. The results obtained from using the 5% WHA are quite similar to those obtained from using 10% silica fume. The 10% WHA replacement ratio can also result in concrete with performance better than the

reference. However, the 15% cannot contribute to strength improvement compared to the control.

Data Availability: No data, models, or code were generated or used during the study.

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