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Performance of Concrete Containing Water-Hyacinth Ash (WHA) as Cement Replacement: Resistance to Elevated Temperature and Seawater Exposures

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Abstract: The current research aims at determining the resistance of concrete mixtures containing the ashes resulting from the water-hyacinth plants [1] as a cement replacement to elevated temperature and to seawater. Two types of water-hyacinth ashes (WHA); burnt in open air and burnt in a closed oven at 600°C for 30 minutes were used as partial replacement materials of ordinary portland cement in concrete mixtures with percentages of up to 15% (by weight of cement). The concrete mixtures were designed with three coarse aggregates types; gravel, dolomite, and basalt. To study the resistance to high temperatures, the specimens were exposed to different elevated temperatures of 200, 400, and 600°C and compared to 25°C as a reference. To investigate the resistance to seawater, three curing regimes were followed; curing in laboratory atmosphere (25°C and 50% relative humidity), immersing in seawater during the entire curing period of one month, and subjecting to drying-wet cycles composed of one-day at laboratory atmosphere and one-day in seawater for a total period of one month before testing. The concrete mixes containing WHA were compared with plain concretes and others proportioned with 10% silica fume. The results revealed significant effect of WHA percentages, coarse aggregates types, and curing methods on the concrete strength. With up to 10% cement replacement with WHA, there was no reduction in strength relative to the reference. The optimal replacement value was around 5%.

Keywords: concrete; durability; high temperature; seawater; silica fume (SF); water-hyacinth ash (WHA)

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1. Introduction

Water hyacinth plants are growing extensively in rivers in Latin America, south and central states of USA, and different worm places in the world, including river Nile in Egypt. It curtails river transports, damages canal walls, increases water evaporation losses, decreases amount of oxygen in water, causes organic pollution in slow moving stream and canals. It is mostly fought by collecting it mechanically and burning it in open air. This method participates significantly to air pollution [1] and large quantities of dried materials on rivers' banks (dry materials constitutes about 28% of the fresh plants). In recent years, many researches were interested in the nutritional values of water hyacinth plants for animal feeds. On the other hand, the nature of water hyacinth plants may predict other applicable uses as reinforcing agents in paper industries [2]. Under controlled burning and sufficiently ground, the water-hyacinth ash (WHA) can be used as cement replacement material in concrete [3,4]. From economic, technological, and ecological points of view, alternative supplementary cementitious materials (ASCM) have an undoubted role in construction industry. These materials can be used in small quantities as inert fillers, or larger quantities if they have pozzolanic properties. Both materials impart technical advantages to the resulting concrete; however,

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the latter enable reducing the significantly the cement, which is costly, consumes natural resources, and negatively affects environment through CO_2 emissions and increasing greenhouse effect [5]. Many of these mineral admixtures are industrial by-products like silica fume and fly ash. Other manufactured pozzolans have a vegetable origin like rice-husk ash, rice-straw ash [6–10].

Concrete durability is closely related, among other factors, to the type of environment in which the concrete has to perform. Fire is one of the natural hazards, which may attack building. The need for heat–resistant building materials is particularly important for structural purposes, especially in the chemical and metallurgical industries and for the thermal shielding of nuclear power plants [11]. On the other hand, the permeability of concrete dictates the rate at which aggressive agents can penetrate and attack the concrete and reinforcing steel bars. The aggressive agents are different and may exist in form of gases (CO_2, SO_2) or liquids (acid rains, acidic water, sulfate–rich water, extra pure water, seawater, etc.).

The WHA has proven success to improve mortar and concrete strengths; however, there are no available reports about its utilization in cement-based materials subjecting to harsh environment conditions. Therefore, it was decided to discuss the influence of using the new pozzolanic material (WHA) as a partial cement replacement in concrete mixtures to resist the deteriorating effects, including high temperatures and seawater. On one hand, the concrete has been extensively used in structures that may subjected to elevated temperature cause by the fire. In such case, the concrete should be designed to resist the deterioration for few hours before complete collapse. On the other hand, cement concrete is finding extensive application in construction of marine structures (coastal and offshore sea structures) either in precast or cast in situ forms as per requirements. A large number of structures can be exposed to seawater either directly or indirectly (e.g., winds can carry seawater spray up to a few miles inland from the coast). In these structures, the effect of seawater on concrete deserves special attention, as the concrete exposes to simultaneous action of several physical and chemical deterioration processes, which provide an excellent opportunity to understand the complexity of concrete durability problems in practice.

To study the resistance to high temperatures, the specimens were exposed to different elevated temperatures up to 600°C, while three curing regimes were followed before testing to investigate the resistance to seawater; curing in laboratory atmosphere, full-time immersion in seawater for a period of one month, and consecutive cycles of one day at laboratory atmosphere and one-day immersion in seawater for a total period of one month. The concrete mixes containing WHA were compared with plain concretes made with pure cement and others proportioned with 10% silica fume.

2. Experimental Program

2.1. Testing Program

A total of 24 concrete mixtures were prepared and tested. The main investigated parameters and their ranges are given in Table 1 of the mix design. Type GU cement, WHA burnt in open air ($WHA_{(0)}$), WHA burnt in closed oven at 600°C for 30 minutes ($WHA_{(600)}$), and silica fume (SF) were considered as binder materials. Three replacement ratios of cement by each the two WHA types (5%, 10%, 15%) and one replacement ratio by SF (10%) were considered in the investigation. Three coarse aggregate (CA) types (gravel, dolomite, and basalt) were also incorporated in the concrete mixtures.

Table 1. Concrete mix design.

Group	Mix no.	Mix proportions (kg/m³)							*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

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	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

The 24 concrete mixtures were tested at the fresh state (slump and unit weight) and at the hardened state (28-day cubic compressive strength (F_{cu}) and 28-day indirect-tensile-splitting strength (F_{sp})).

The durability aspects of WHA concretes were evaluated through the determination of the losses in compressive strength due to the exposure to different elevated temperatures and to dry-wetting cycles of seawater. This was realized on cubic specimens.

Resistance of concrete to high temperatures – After 28 days of moisture curing (lime-water path at 23°C), the concrete specimens were kept at laboratory atmosphere (23°C and 50% relative humidity (RH)) until the age of 91 days. The specimens were then dried at a 105±5ºC for 24 hours in electric furnace. To evaluate the resistance of concrete to high temperatures, the concrete specimens were exposed to the target high temperatures of 200ºC, 400ºC, and 600ºC for a duration of three hours. The heat-treated samples were cooled slowly to room temperature before testing. The results were compared with concrete mixtures remained at the laboratory atmosphere (23°C and 50% RH).

Resistance of concrete to dry-wet cycles of seawater – Concrete exposed to sea water is wetted by a solution of salts – principally sodium, chloride, and magnesium sulfate. In such case, damage to concrete usually results from failure to use good practices in concrete construction. Magnesium sulfate may attack most, if not all, of the constituents of hardened portland cement paste, especially the aluminate constituent; chlorides may promote corrosion of steel; and alkalis may participate in alkali-aggregate reaction.

After the 28-day moisture curing (lime-water path at 23°C), the concrete specimens were kept at laboratory atmosphere (23°C and 50% RH) until the age of 58 days. To investigate the resistance to seawater, three curing regimes were evaluated. In first case, the specimens were kept at laboratory atmosphere for another 32 days (from the age of 58 to 90 days), and was considered as control. In second case, the specimens were stored in seawater for a period of 32 days. In third case, the specimens were subjected to drying-wet composed of one-day at laboratory atmosphere and one-day in seawater for same period of 32 days. The concentration of the major ions in the seawater used in this investigation are listed in Table 2. The chemical composition of the seawater is characterized by the presence of about 3.5% soluble salts by wt. The ionic concentrations of Na^{+} and Cl^{-} are the highest, typically 12,000 and 21,000 mg/liter, respectively. However, from the standpoint of aggressive action to cement hydration products, sufficient amounts of Mg^{++} and SO_4^{--} are present, 1500 and 2600 mg/liter, respectively. The average value of the pH of the seawater is around 8.2.

Table 2. Major constituents of seawater (% wt. of dissolved materials).

Constituent	Symbol	Percentage %	Concentration (mg/l)
Sodium	Na^{++}	30.61	124000

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Magnesium	Mg^{++}	3.69	1500
Calcium	Ca^{++}	1.16	470
Potassium	K^{+}	1.10	445
Strontium	Si ++	0.03	12
Chloride	Cl^{-}	55.04	21270
Sulphate	SO_4^{--}	7.68	2596
Bicarbonate	HCO_3^{-}	0.41	165
Bromine	Br^{-}	0.19	77

These results were experimentally determined at the Department of Chemistry, Faculty of Science, Minoufia University.

2.2. Materials

Type GU cement was used in all mixtures. The SF obtained from a silicon company in Cairo Egypt was used in certain mixtures at a replacement level of 10%. Chemical and physical properties of cement and SF (provided by 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

Gravel, dolomite, and basalt as coarse aggregates (CA) with maximum-nominal size of 25 mm, as well as natural siliceous sand as fine aggregate (FA), with the physical and mechanical properties shown in Table 4, were incorporated in the mixtures. 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 fine 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

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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 investigated WHA. Two burning methods for producing the WHA were followed; burning in open air for 60 min ($WHA_{(0)}$) and in a closed oven at 600˚C for 30 min ($WHA_{(600)}$). The complete preparation processes are summarized in [3]. The two WHA types are presented in Fig. 1.

(a) Burnt in open air water-hyacinth ash

(b) Burnt-in-oven at 600°C water-hyacinth ash

Figure 1. Fresh and dried water hyacinth plants, and water-hyacinth ashes (WHA).

The physical and chemical characterization of the two WHA types 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 [12]. 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 Fig. 2. 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.

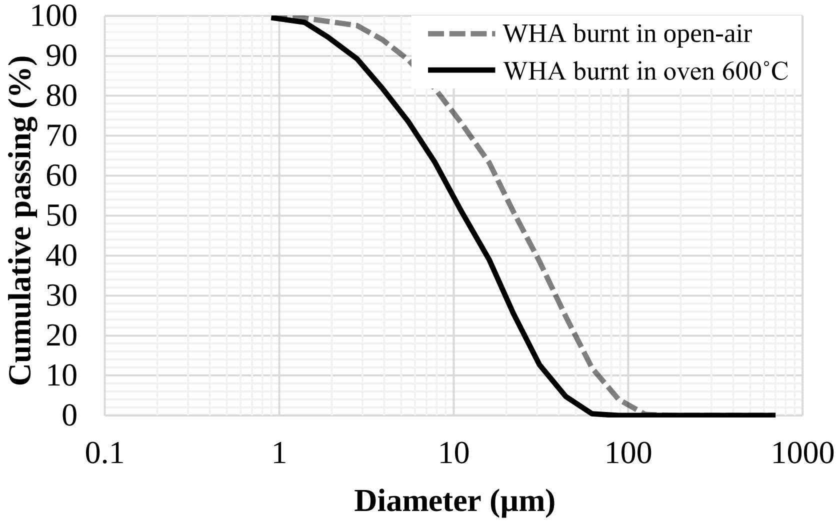

Figure 2. Particle-size distribution of water-hyacinth ash (WHA) burnt in open air and closed oven at 600 °C.

The scanning-electron microscope (SEM) photography using SEM model Philips XL30 attached with EDX unit carried out on the WHA revealed that the WHA is porous and mainly contained angular particles of irregular shape and rough textures, with few spherical particles of smooth surfaces similar to the OPC particles [3,13].

2.3. Mixture Proportions, Mixing Sequence, Samples Preparation, and Curing Conditions

All concrete ingredients were kept at 23°C for 24 hours prior mixing. The cementitious materials content 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 1.

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). Cylindrical specimens measuring 100 x 200 mm were prepared for measuring the F_{sp} (ASTM C496).

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 moulds were then placed on a vibrating table for 30 seconds before surface finishing. The specimens were kept in the moulds at a temperature of about 23°C and a RH of 50% for 24 hours before demolding and storing in lime-water path at 23°C until the age of 28 days. 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.

3. Results and Discussions

3.1. Fresh Concrete Properties

3.1.1. Workability

The workability of the concrete mixtures was measured using slump cone, and the results are shown in Table 5. When WHA or SF was introduced into the concrete, the workability decreased. The results showed also more slump loss with increasing the WHA replacement ratio. The WHA of the porous, angular, irregular shape, and rough textures particles required higher water content

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compared to the cement particles. 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 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 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 cement. This increased the friction between the solids in the paste in the case of the WHA/cement 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 workability loss.

Table 5. Fresh concrete properties.

Materials	Slump (mm)			Unit weight (kg/m³)		
	Gravel	Dolomite	Basalt	Gravel	Dolomite	Basalt
OPC	105	100	135	2364	2493	2527
$WHA_{(0)}$5%	95	92	123	2361	2490	2524
$WHA_{(0)}$10%	87	77	110	2358	2487	2521
$WHA_{(0)}$15%	80	67	97	2355	2483	2517
$WHA_{(600)}$5%	92	85	120	2362	2490	2525
$WHA_{(600)}$10%	85	70	105	2359	2488	2522
$WHA_{(600)}$15%	75	60	90	2357	2486	2520
SF 10%	55	40	60	2354	2482	2516

Relative to the control mixture, the slump losses for the concretes containing $WHA_{(600)}$ were slightly higher than those of the concretes containing $WHA_{(0)}$, 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.

3.1.2. Unit Weight

The unit weight results of the evaluated concrete mixtures are given in Table 5. 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 cement 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 cement, $WHA_{(600)}$, $WHA_{(0)}$, and SF were 3.13, 2.65, 2.52, and 2.2, respectively.

3.2. Hardened Concrete Results

3.2.1. Cubes Compressive Strength (F_{cu})

The results of the 28-day F_{cu} are shown in Fig. 3 for three types of coarse aggregates; gravel, dolomite, and basalt.

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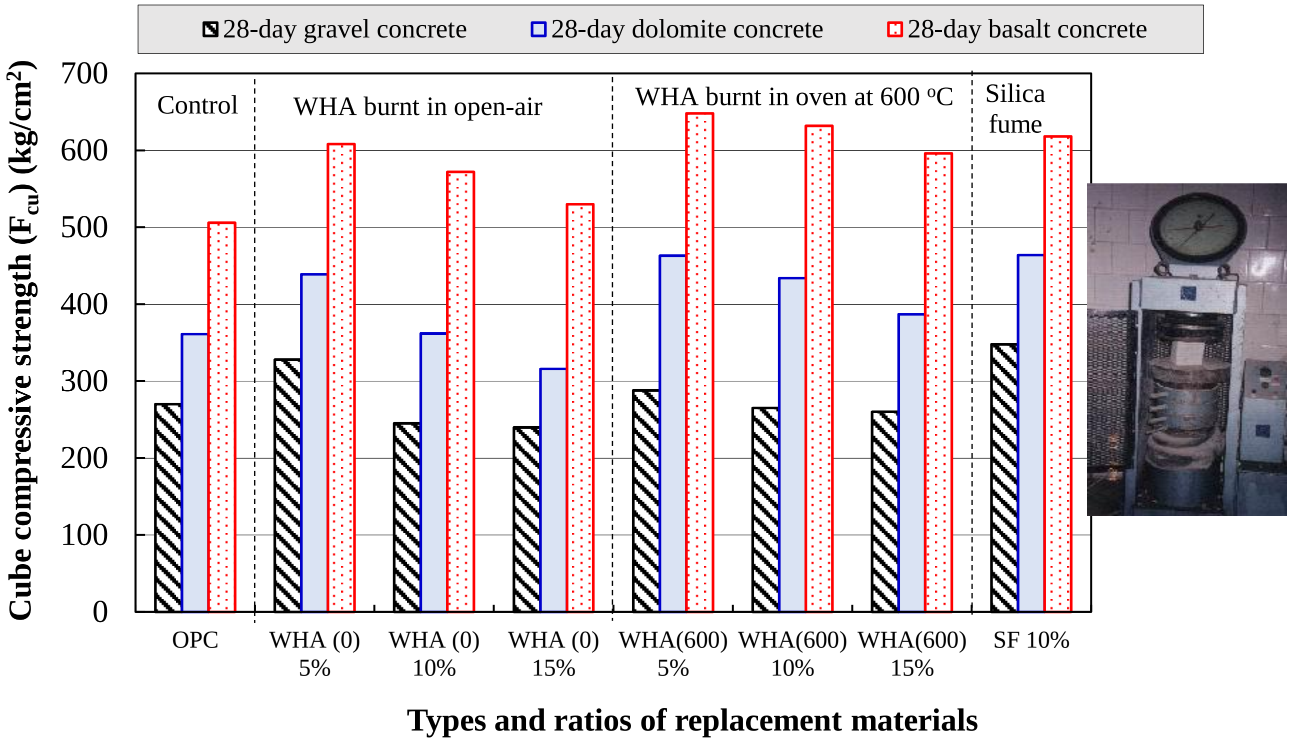

Figure 3. Cube compressive strength (F_{cu}) for investigated concrete mixtures at 28 days.

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 $WHA_{(600)}$. The concrete made with 5% WHA in some cases were found similar or greater than the concrete containing 10% SF. These findings are similar to the results obtained in [4,14].

The controlled burning process of the WHA in an oven at 600°C showed to be slightly more effective than the open-air burning on the F_{cu}. The F_{cu} of the $WHA_{(600)}$ concretes were slightly higher than those made with $WHA_{(0)}$ with little variations. This can be due to the small variations in the fineness between the two ashes.

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.

Through visual inspection, the failure pattern of cubes after compressive test for the different mixes containing WHA are classified as non-explosive failure. However, the pattern of failure for the control mix and the mix containing SF showed explosive failure modes. It can also be seen that most of the cube specimens incorporating WHA showed the cracking to be at approximately 45°to the axis near the ends.

3.2.2. 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 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 investigated 24 concrete mixtures are illustrated in Fig. 4.

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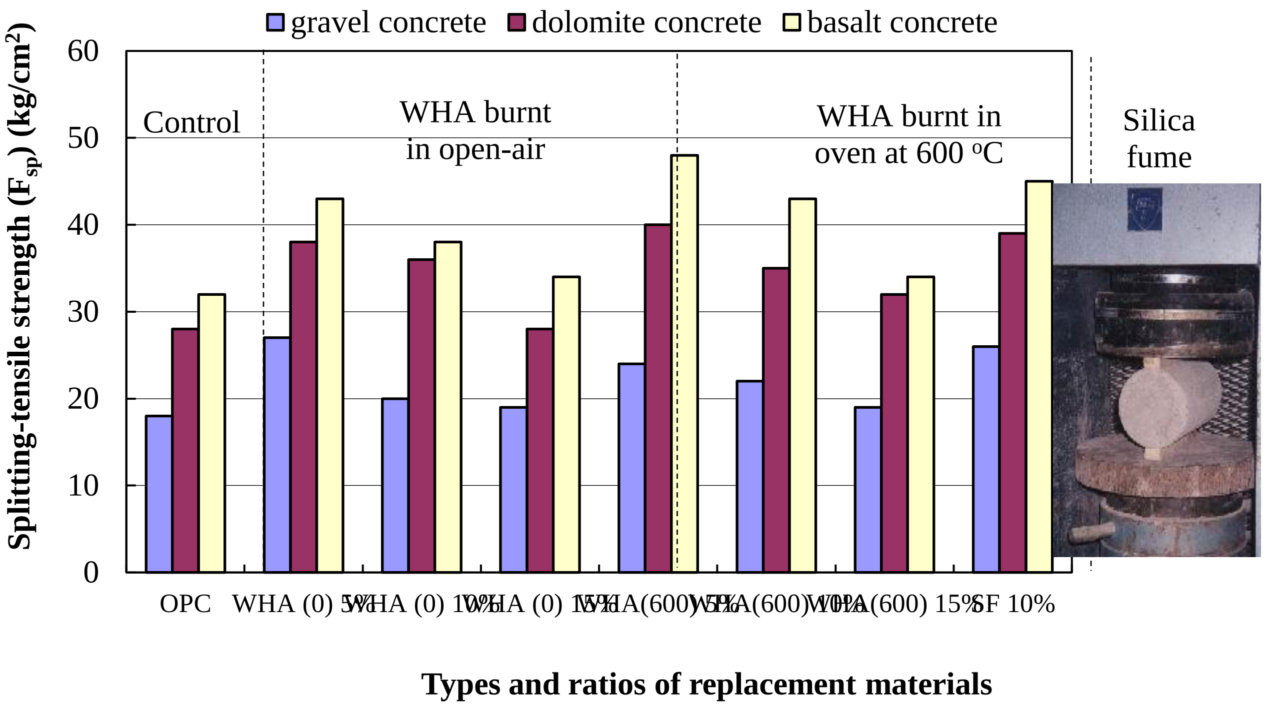

Figure 4. Splitting-tensile strength (F_{sp}) (after 28 days of curing) for investigated concrete mixtures.

The F_{sp} for the concrete mixtures made with WHA at all replacement ratios were greater than the control concrete. 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 the concrete mixtures containing 10% SF (the increase ranged between 39% and 44%). These findings are similar to the results obtained by other researchers [14]. 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. Even at 15% WHA replacement, the increase in the F_{sp} was about 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.

The cylinder specimens after cylindrical splitting tensile strength test exhibited fracture surfaces.

3.3. Resistance to High Temperatures

The effect of elevated temperature on mechanical performance of concrete depends on all concrete ingredients, including type and content of cement, cement replacement materials, admixtures, and aggregates. Figure 5 shows the effect of different treatment temperatures on compressive strength of the investigated concrete mixtures containing different cementitious materials (cement, WHA, and SF) and different types of coarse aggregates (gravel, dolomite, and basalt).

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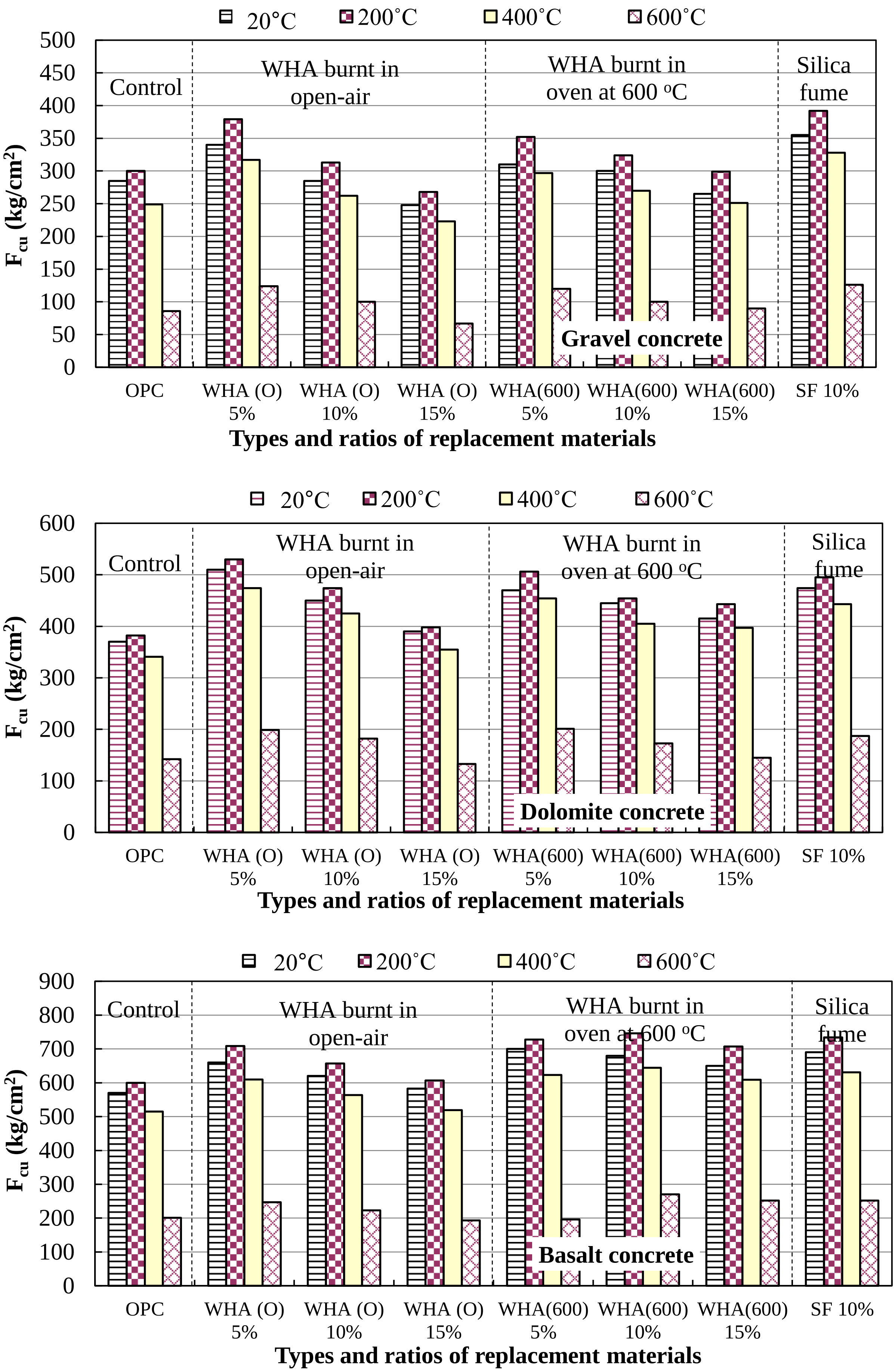

Figure 5. Effect of high temperatures on cube compressive strength (F_{cu}) for investigated concrete mixtures.

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In general, the WHA concretes showed the highest resistance to elevated temperatures. This may be due to the higher thermal stability of concrete containing WHA than that of the reference concrete. At 200˚C, the compressive strength has been increased and reached about, for gravel concrete, 5%, 14%, and 10%, for dolomite concrete, 3%, 8%, and 4%, and for basalt concrete, 5%, 10%, and 6%, for reference, 5%WHA$_{(0, 600)}$, and 10% SF, respectively. These results are associated with the formation of more C-S-H hydrates with stronger binding forces and sufficient thermal stability during the heat treatment. As temperature increased to 400ºC, the compressive strength decreased for all concrete mixtures. The 600˚C temperature caused a major decrease in compressive strength, due to the disruption of the structure of the cementitious components under the effect of high temperature. The WHA concretes remained again the best in resisting this high temperature. The drops in the compressive strength recorded for the gravel concretes were 70%, 61%, and 65%, for the dolomite concrete were 62%, 57%, and 61%, and for the basalt concrete were about 65%, 60%, and 64% for the reference, 5%WHA$_{(0, 600)}$, and 10% SF, respectively. In this study, we can assume that the aggregate is thermally stable within the temperature range of exposures. The unstable component of the concrete under investigation is the portland cement paste. Heterogeneity of concrete due to its components, both in micro and macroscale, causes a large number of phenomena and physico-chemical processes during heat treatment. Therefore, the moisture is removed at a faster rate which affects the surrounding phase of cement paste when exposed to high temperatures. Mainly due to flow resistance and high temperature, steam creates a high pressure in the paste. In consequence, the so-called conditions for internal autoclaving are formed in cement paste. The temperature range between l00-300°C is the most favourable for the formation of such conditions because in this temperature range steam is liberated most intensively [15]. Additional hydration of unhydrated cement grains is the results of steam effect under the condition of internal autoclaving. This is indicated by a decrease in phases (C_3S + β-C_2S) and an increase in the Ca(OH) phase due to recrystallization of the amorphous Ca(OH) into more C-S-H.

Obviously, the concrete specimens made with 5% WHA, as cement replacement, possessed the highest strength at all temperatures during heat treatment relative to the reference. The addition of 10% WHA has proved also efficiency relative to the reference, but less than the 5% WHA. However, the situation was reversed when the replacement was more than 10% WHA. These results agree with those reported in the review [15,16]. These results can be related to the relative porosity of concrete at the various treatment temperatures. Generally, the porosity increases with increasing the temperature during the thermal treatment. So, the higher resistance to fire is mainly associated with the formation of a denser internal concrete structure when incorporating 5-10% WHA, resulting higher thermal stability. With increasing the WHA content in concrete, higher porosity values were obtained. This result is related to the formation and enlargement of microcracks and/or the increased degree of crystallinity of the formed hydrates leading to a sort of opening of the pore system of concrete specimens. As the WHA increases from 0 to 10%, larger amounts of C-S-H can be formed due to the decomposition of the cement hydrates. However, the concrete made with 15% WHA, there is no more C-S-H can be formed and the excess WHA remains free in the concrete medium.

The reduction in compressive strength due to the exposure to high temperatures for the dolomite concretes was higher than that for the basalt concretes and gravel concretes. This may be associated to the differences in the thermally stability values of the various coarse aggregates types used in this study at the various exposure temperature.

3.4. Resistance to Seawater

The factors inherent in seawater exposure that influence concrete are wetting and drying, chemical reaction of chlorides, sulfates, and alkalis (sodium and potassium), and in some instances, dissolved carbon dioxide. The SO_4^{--} and Mg^{++} are also harmful constituents in seawater; sulfate attack is classified as severe when the SO_4^{--} ion concentration is higher than 1500 mg/l; similarly, Portland cement paste can deteriorate by cat–ion-exchange reactions when Mg^{++} ion concentration exceeds, for

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instance, 500 mg/l. The seawater used in the current study had SO_4^{-} and Mg^{++} concentrations of around 2600 and 1500 mg/l, respectively, as indicated in Table 2).

The percentage of decrease (relative to the dry curing at the laboratory atmosphere) in F_{cu} due to the exposure to wet-dry cycles of seawater (1 day in seawater and 1 day at laboratory atmosphere for a total period of 32 days – *intermittent immersion*) and to the full exposure to seawater for a total period of 32 days (*continuous immersion*) are shown in Figures 6 and 7, respectively. The concrete mixtures containing different percentages of $WHA_{(0)}$ and $WHA_{(600)}$ were compared to a reference concrete mixture made only with cement and with 10%SF. The choice of these two exposure conditions were selected for various technical reasons which can detailed, as follows.

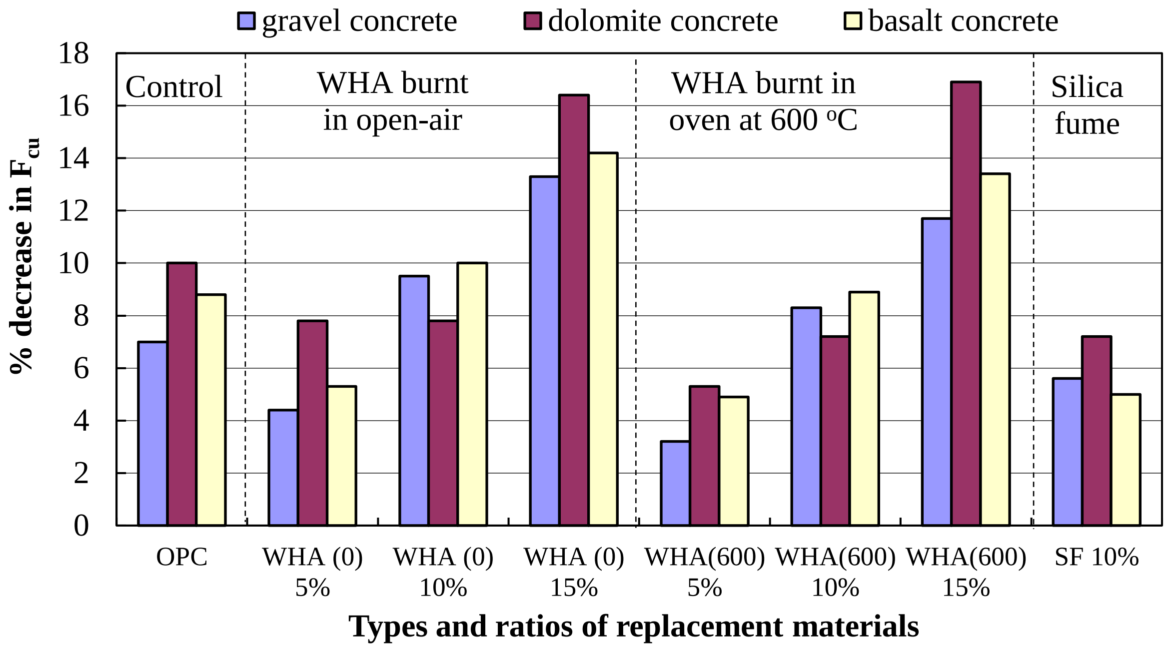

Figure 6. Percentage of decrease (relative to the dry curing at the laboratory atmosphere) in cube compressive strength (F_{cu}) due to the *intermittent immersion* in seawater for a total period of 32 days.

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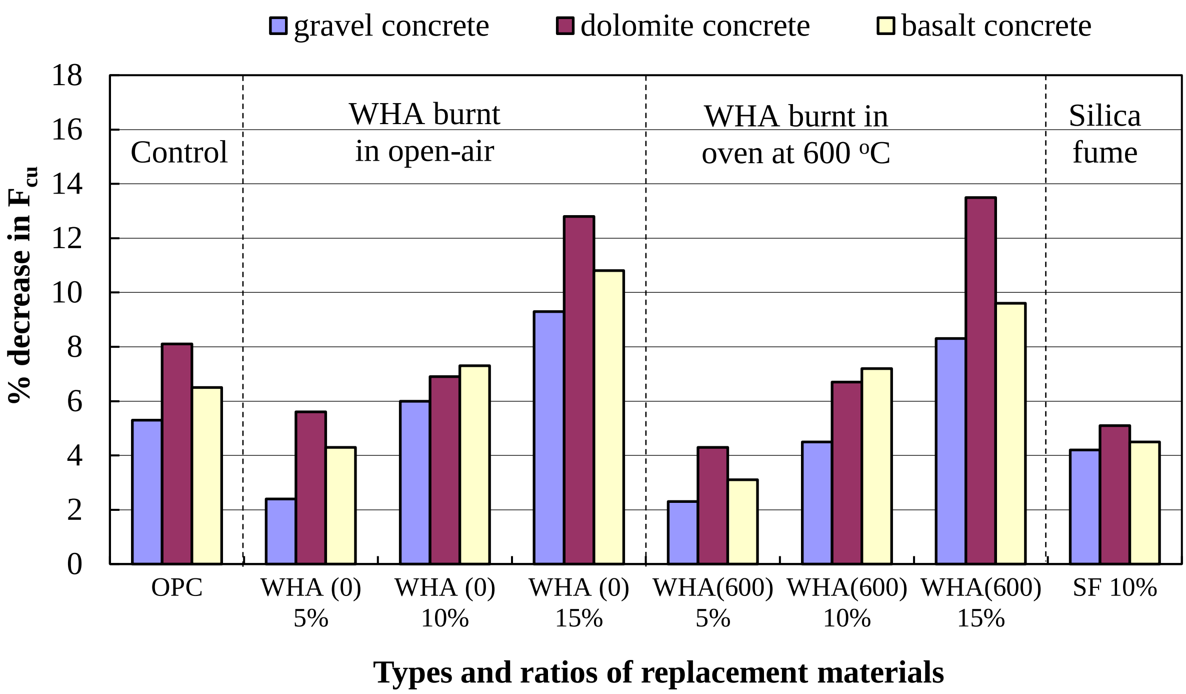

Figure 7. Percentage of decrease (relative to the dry curing at the laboratory atmosphere) in cube compressive strength (F_{cu}) due to the *continuous immersion* in seawater for a total period of 32 days.

3.4.1. Effect of Continuous Immersion of Concrete in Seawater

Concrete that is totally and continuously immersed in water, even if the water contains dissolved salts such as are found in seawater, generally may be regarded as being in a protected exposure. Continuous immersion usually provides a uniformity of environment with respect to temperature and moisture content that prevents the immersed concrete from being subjected to such deteriorating influences as frost action, volume change due to wetting and drying, and differential volume change due to moisture content differences between the surface and the interior. Continuous immersion also tends to reduce the potential for chemical reaction by removing changes in degree of saturation as a mechanism for the flow in and out of the concrete of solutions containing ions that can attack concrete constituents, and leaving only concentration gradients as the means of ingress of such ions. Locher and Pisters [18] noted that under equal conditions of exposure, the aggressiveness of water increases with increasing concentration of the relevant substances, but that aggressiveness is also increased by higher temperatures, higher pressures, wetting and drying, or mechanical abrasion by fast-flowing or turbulent waters.

3.4.2. Effects of Intermittent Immersion of Concrete in Seawater

Most concrete structures exposed to seawater are partially or wholly situated so that they are sometimes immersed in seawater and sometimes exposed to air. If the structure is located where the temperatures fall below freezing, then the concrete that is exposed to the air with falling tide is probably subjected to as severe frost action as is any concrete in natural exposure. The second important effect on concrete related to wetting and drying is the volume change relations due to changes in, or changes in uniformity of, moisture content. These phenomena, often referred to as "drying shrinkage" effects.

The obtained results confirmed these observations. It can also be seen from the results in Figs. 6 and 7 that the decrease in the F_{cu} of the concrete mixtures with the intermittent immersion in seawater was greater than the decrease in the F_{cu} of the concrete mixtures with the continuous immersion in seawater. This can be illustrated in in the relationship in Fig. 8.

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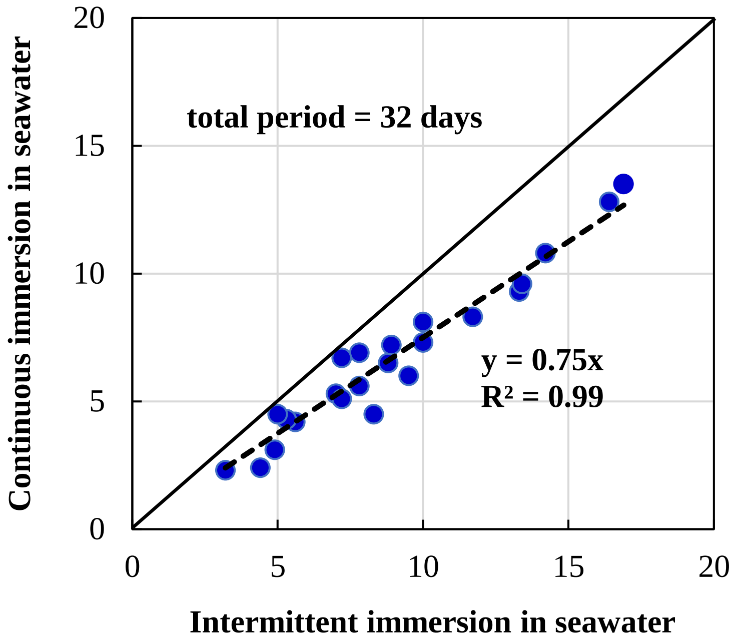

Figure 8. Correlation between the reduction in cubic-compressive strength (F_{cu}) of the intermittent versus the continuous immersions in seawater.

The results revealed also that the WHA concretes presented higher resistance to seawater compared to reference with 100% cement. For example in the case of intermittent immersion and for reference, 5%WHA$_{(0)}$, 5%WHA$_{(600)}$, and 10% SF concretes, respectively, these reductions were about 7%, 4%, 3%, and 6% for the gravel concretes, 10%, 8%, 5%, and 7% for the dolomite concretes, 9%, 5%, 5%s and 5% for the basalt concretes. The respective values in the case of continuous immersion and for the reference, 5%WHA$_{(0)}$, 5%WHA$_{(600)}$, and 10% SF concretes, respectively, these reductions were about 5%, 2%, 2%, and 4.2% for the gravel concretes, 8%, 6%, 4%, and 5% for the dolomite concretes, 7%, 4%, 3%, and 5% for the basalt concretes. Other general observations are; (1) the decrease in F_{cu} of WHA and SF concretes was inferior than the decrease in F_{cu} of reference concrete, (2) the decrease in the F_{cu} of the concrete mixtures containing 5%WHA$_{(600)}$ or 5%WHA$_{(0)}$ were lower than the decrease in the F_{cu} of the reference concrete and in most cases than SF 10% concrete. The 5%WHA replacement ratio could be considered the best ratio resulting in the best resistance to seawater exposure, and (3) the decrease in the F_{cu} of the concrete mixtures contained 10% and 15% WHA$_{(600)}$ and 10% and 15% WHA$_{(0)}$ were higher than the decrease in the F_{cu} of the reference and the 10%SF concrete mixtures.

The use of proper dosage of WHA in concrete mixture can densify the concrete microstructure, leading to a reduction in the porosity and an improvement in permeability and strength. This can be related to the role of the WHA in filling the voids between concrete particles. By doing so, the concrete structure can better prevent the seawater from penetrating inside the concrete. The use of pozzolans in concrete to be exposed to seawater has been recommended because of the observations stating that their use increases the resistance of the concrete to chemical attack to the seawater. Lea [19] reviewed the various explanations that have been offered for this effect. The explanations include: (1) reduction in amount of free calcium hydroxide, by reaction with pozzolan, thus reducing the degree to which the reaction of sulfates and calcium hydroxide can occur; (2) increased solubility of hydrated calcium aluminates with decreased concentration of calcium hydroxide, and hence greater likelihood that the sulfate-aluminate reaction will take place through solution rather than in the solid state and thus produce less expansion; (3) decreased tendency of the low-sulfate calcium-aluminum sulfate to convert to the high-sulfate form (ettringite) as the concentration of calcium hydroxide in solution decreases, due to the higher sulfate concentration required to effect the conversion as such decrease occurs; (4) decreased permeability of the concrete with reduced rate of entry of sulfate solution; (5) formation of lime-pozzolan reaction product films that protect the hydrated calcium aluminate; and (6) decomposition of lime-pozzolan reaction products by seawater to leave silica and alumina gel which are more stable products.

The expansive hydraulic cement (ASTM C845) [20] has received attention for concrete construction in marine exposures. Concretes made with expansive cement may be controlled to achieve shrinkage compensation, resistance to cracking, reduced permeability, and wear resistance. Such properties may help to render wharf decks crackproof, waterproof, and hence more wear-resistant. Expansive-cement concrete should further enhance the resistance to seawater of both reinforced and prestressed concrete piles for waterfront applications. The WHA could give a tendency like the expansive cement, because the WHA can increase the percentage of the Al_2O_3 of the WHA/cement blend as it possesses higher percentage of Al_2O_3 than cement.

The decrease in the F_{cu} for the concretes containing $WHA_{(600)}$ was slightly lower than the decrease in the F_{cu} of the concretes containing $WHA_{(0)}$. This can be due to the small variations in the fineness between the two ashes.

It can also be seen from the results that, the reduction in the F_{cu} due to immersed in seawater for the gravel concrete was less than the reduction reported in F_{cu} for the basalt concretes, while the dolomite concretes placed the third. This is referred to the relative crushing strengths and the surface texture of different aggregates.

4. Conclusions

The main conclusions derived from this study can be summarized as follows:

1. During the manufacture of water-hyacinth ash (WHA), burning the dried water-hyacinth plants in closed ovens produces ash with no effect on environment and with high silica content than burning in open air.
2. The use of WHA as a cement replacement material can provide distinguished increase to concrete strength, and the resistance of elevated temperatures and seawater.
3. The addition of WHA to ordinary concrete leads to the consumption of Ca(OH) obtained during cement hydration and forming more C-S-H of stronger binding forces and a sufficient thermal stability, resulting in a concrete with densified microstructure and of lower porosity and permeability. Concrete made with 5% to 10% WHA possess the higher compressive strength compared to reference, with more particular attention when exposed to thermal treatment at elevated temperatures.
4. Deterioration of concrete exposed to seawater is mainly due to chemical action (change in composition of cement by chlorides and sulfates present in seawater). Selecting suitable cementitious materials with pozzolanic-based effects such as WHA can ensure densified and impermeable concrete product with higher resistance to seawater attack.
5. WHA at a 5% replacement ratio to cement is the optimum, 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 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.
6. Using water hyacinth as cement replacement material in concrete participates in keeping the environment clean, while reducing natural resources of cement manufacture.

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