Chapter

The Use of Ceramic Waste Powder (CWP) in Making Eco-Friendly Concretes

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Abstract

The global production of ceramic waste powder (CWP), which is produced during the final polishing process of ceramic tiles, exceeds 22 billion tons. The disposal of CWP in landfills will cause significant environmental problems (i.e., soil, air, and groundwater pollution). CWP is characterized by its chemical composition that is mainly composed of silica (SiO_2) and alumina (Al_2O_3). Both minerals represent more than 80% of the CWP composition. CWP has potentials to be used as an ingredient to partially or entirely replacing Portland cement to make eco-friendly concretes. This chapter summarizes the effect of using CWP in making eco-friendly concretes, with a particular focus on using CWP as a partial cement replacement in conventional-vibrated concrete (CVC) and self-compacting concrete (SCC), and the production of zero-cement alkali-activated concrete (AAC).

Keywords: ceramic waste powder, cement replacement, eco-friendly concrete, durability, microstructure

1. Introduction

In a rapidly growing world population and toward meeting consumers' needs, solid waste landfills will continue receiving huge volumes of waste. Therefore, waste management is becoming increasingly mandatory for the promotion of environmental sustainability. Numerous regulations have been imposed worldwide by governments and environmental organizations in order to reduce the negative environmental impact resulting from large numbers of solid waste landfills. The transformation of a large amount of solid waste into an alternative resource will preserve the reducing nonrenewable resources of materials; maintain the required energy and also will help solve environmental and exhausted landfill problems. Until today, researchers are investigating new solid waste materials and the potentials of recycling either in other industries or new products.

Being the world's most consumed human-made material, concrete attracted considerable interest as a possible way to recycle solid waste products especially those that can replace cement which is a significant contributor to global greenhouse gas emissions. An equal amount of CO_2 is generated for the production of Portland cement [1]. The cement industry produces around 5–8% of the annual global greenhouse gas emissions released into the atmosphere [2]. Several by-products such as fly ash, slag, and silica fume are effectively being used in the daily production of concrete as partial cement replacement (i.e., supplementary cementitious materials (SCM)) to reduce CO_2 emission [3, 4].

Global production of ceramic tiles is more than 12 Billion m^2 [5]. The manufacture of ceramic tiles generates ceramic waste powder (CWP) during the final polishing process at a rate of 19 kg/m^2 [6]. Therefore, the global generation of CWP exceeds 22 Billion tons. The CWP represents a significant challenge to get rid of concerning its environmental impact. It can cause, soil, water, and air pollution. On the other hand, it could represent an excellent opportunity to be used as an alternative concrete ingredient if it could be utilized in making concrete.

The effect of using ceramic wastes (i.e., roof tiles, blocks, bricks, electrical insulators, etc.) as aggregates or SCM in conventional-vibrated concrete (CVC) and mortar was reported in several studies. It is noted that limited studies were conducted on using CWP as a cement replacement in self-compacting concrete (SCC) and alkali-activated concrete (AAC) (i.e., geopolymer concrete). Some studies investigated the use of ceramic waste as coarse aggregates in CVC and mortar [7–16]. It was concluded that ceramic waste could be used as partial replacement of natural coarse aggregate. The ceramic waste aggregate should be pre-saturated by water to offset its high absorption. The compressive strength decreased if the ceramic waste replaced natural coarse aggregate beyond 25% by weight. The use of ceramic waste as fine aggregate in CVC and mortar was assessed by various researchers [16–22]. It was noted that using a high content of ceramic waste as fine aggregate had a negative impact on the workability of the fresh concrete, and workability admixtures were needed to avoid any adverse effect on concrete workability. It was concluded that the use of 50% by weight replacement of fine natural aggregate by ceramic waste could produce concrete without affecting the performance of hardened concrete.

The use of CWP as partial replacement of cement attracted the attention of several researchers [6, 23–35]. The main conclusion from the studies was that CWP showed slow pozzolanic activity which was evidenced at late ages. The early compressive strength was reduced by the inclusion of CWP. The development of compressive strength needed time. On the other hand, durability was improved by the incorporation of CWP in the mixtures. It was noticed that the investigations on using CWP as partial replacement of cement did not address the fresh concrete properties as affected by the inclusion of CWP as well as the microstructure characteristics. Also, no guidelines were provided for using CWP to partially replace cement. The CWP replacement level will depend on personal knowledge and experience. Furthermore, the replacement of cement by large quantities of CWP needs further evaluation.

The use of CWP in self-compacting concrete (SCC) mixtures received limited attention. In 2017, Subaşi et al. [36] investigated the use of CWP as a partial cement replacement in SCC mixtures. It was concluded that CWP could replace 15% by weight of the cement without adversely affecting the properties of the produced SCC. In 2018, Jerônimo et al. [37] replaced cement by ground clay brick waste (GCBW) in SCC mixtures. It was concluded that 20–30% by weight of the cement could be replaced by GCBW, and the compressive strength improved at 90 days of age. It was observed that the detailed evaluation of the SCC fresh properties as affected by the inclusion of CWP was not addressed. Also, the effect of using high-volume CWP in SCC still needs further assessment.

Concerning using CWP in alkali-activated concrete (AAC) (i.e., geopolymer concrete), it was noted that very limited investigations were conducted [38–40]. The main conclusion that CWP could be used in making AAC but needs detailed investigation and assessment.

An in-depth investigation to study the utilization of CWP in the production of different types of concrete is needed. This chapter summarizes the findings of collective studies conducted by the authors investigating the use of CWP in making eco-friendly concrete [41–45], with a particular focus on using CWP as a partial cement replacement in CVC and SCC, and the production of AAC. This will establish better understanding on how to incorporate an existing solid waste as a new construction ingredient in making echo-friendly concretes in order to optimize solid waste management, and help protect the environment by reducing the use of cement and efficiently getting rid of a solid waste material.

2. Characteristics of CWP

The produced ceramic waste material was a wet material due to the use of water during the polishing process. The average moisture content was 36% by mass. The average specific surface area (SSA) measured by air-permeability (i.e., Blain air permeability test apparatus) was 555 m^2/kg. More than 50% by volume of the CWP particles had a size ranging between 5 and 10 μm. **Figure 1** shows the particles' size distribution of the CWP.

The CWP consisted of irregular and angular particles which are similar to cement particles in shape as shown in the scanning electron microscope (SEM) image in **Figure 2**. **Figure 3** shows the energy dispersive spectroscopy (EDS) of the main oxides of the CWP. The EDS analysis indicated that CWP is mainly composed of SiO_2 and Al_2O_3.

Table 1 gives the chemical analysis of the CWP as determined by X-ray fluorescence (XRF). CWP is mainly composed of silica (SiO_2) and alumina (Al_2O_3). Both oxides are around 85% of the total material mass. Other compounds (i.e., CaO, MgO, and SO_3) exist in small quantities. The mass fractions of (SiO_2 + Al_2O_3 + Fe_2O_3) satisfies the requirement of the ASTM C618 [46] for natural pozzolana (i.e., >70%). Also, the SO_3 and the loss on ignition (L.O.I.) conformed to the ASTM C618 requirements.

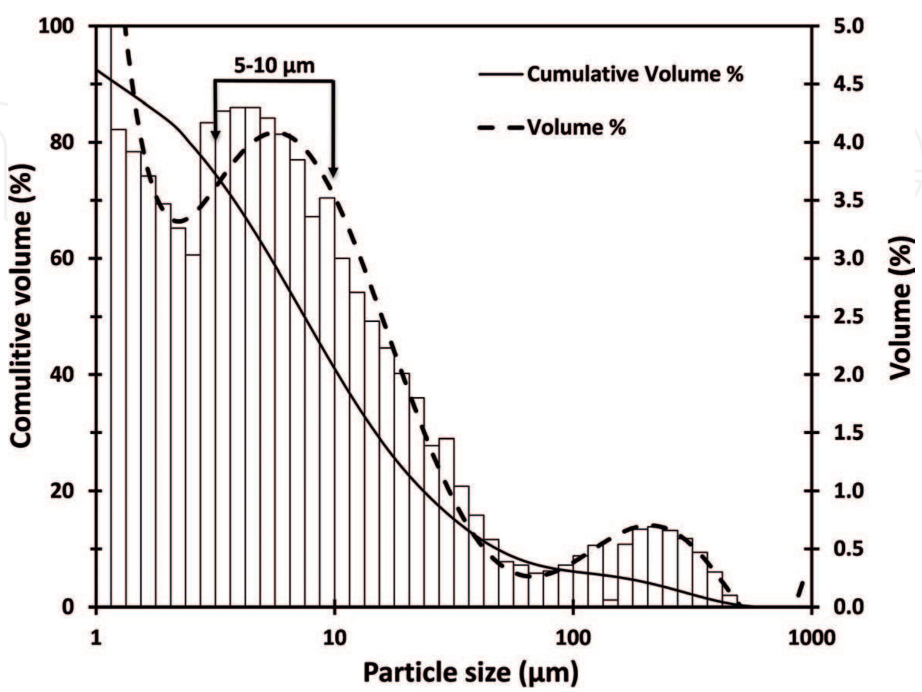


Figure 1.
Particle size distribution of CWP [43]. Reproduced with permission from the publisher.

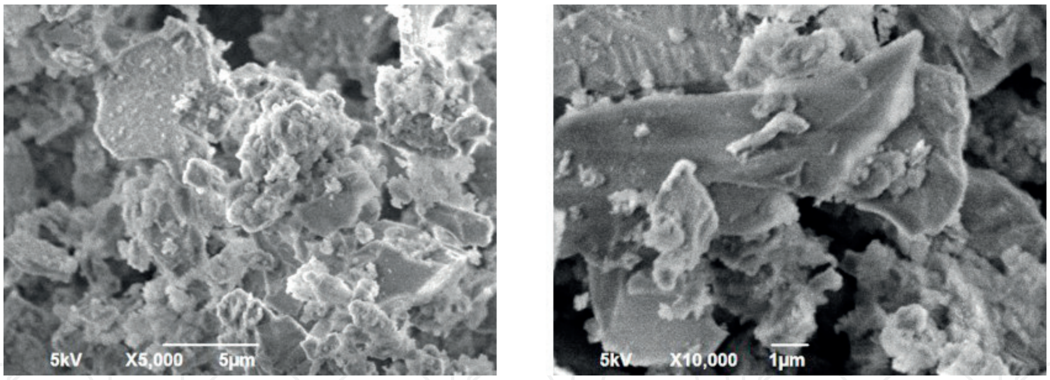
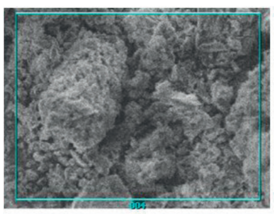
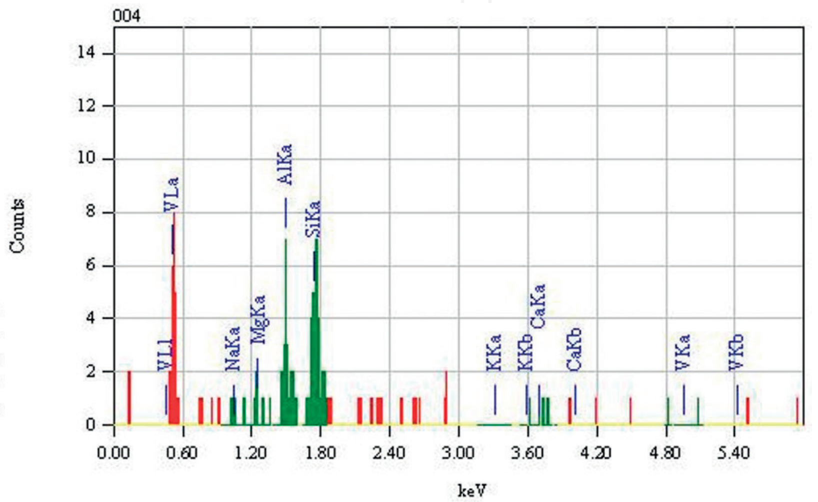
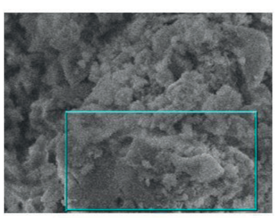


Figure 2.
SEM images of CWP.



Element	(KeV)	Mass %
Na	1.041	3.03
Mg	1.253	4.84
Al	1.486	28.46
Si	1.739	61.89
K	3.312	0.16
Ca	3.690	1.61





Element	(KeV)	Mass %
Na	1.041	3.43
Mg	1.253	4.65
Al	1.486	15.00
Si	1.739	64.34
K	3.312	4.98
Ca	3.690	7.59

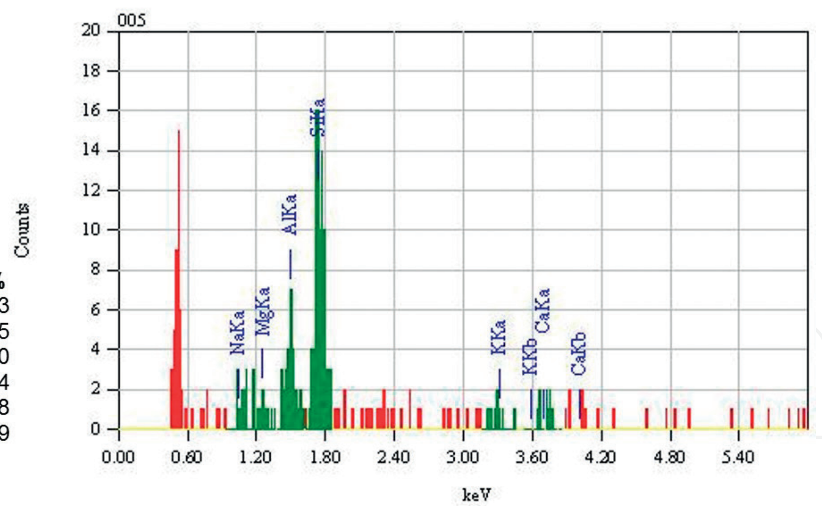


Figure 3.
EDS analysis of CWP [43]. Reproduced with permission from the publisher.

Figure 4 displays the X-ray diffraction (XRD) analysis of the CWP. The XRD indicates that the main peaks were noticed between 2-theta values of 20 and 30° which indicates the presence of (SiO_2). The observed hump between 20 and 30° indicates the occurrence of an amorphous phase. Moreover, the unleveled graph trend between the 2-theta values 0 and 40° indicates the existence of an amorphous phase in the CWP sample.

Characterizing industrial waste materials and their potentials is one of the challenging issues in the field of cement and concrete. The compressive strength was given prominence as an initial means for evaluating the pozzolanic activity. The compressive strength development of cement mortar including CWP is assessed according to ASTM C311 [47] to measure the strength activity index (SAI).

Four mortar mixtures are prepared in which cement is partially replaced by CWP. The replacement levels are 10, 20, 30 and 40% by weight. Strength activity index (SAI) is calculated as the strength percentage as compared to the control mortar mixture. **Table 2** gives the 28 days compressive strength, standard deviation SAI. Results showed that all CWP specimens satisfied the ASTM C618 requirement of SAI (i.e., >75%). In an investigation by Steiner et al. [25], a similar trend in the activity index for mortar mixtures with ceramic tiles polishing residues was reported. The SAI decreased after the inclusion of 40% CWP by cement mass; this could be attributed to the dilution effect. Also, it might be due to the high silica available in the mixture as a result of the high CWP. This large quantity could not find sufficient calcium hydroxide (CH) in order to react with. Therefore, most of the silica components were left without getting involved in the chemical reaction [48]. Also, Frattini test [49] is performed to identify the pozzolanic activity of CWP following BS EN 196-5:2011 [50]. Test samples with 0, 20 and 40% CWP as cement replacement by weight are tested. The Frattini test showed that concrete with 20

CaO	SiO_2	Al_2O_3	MgO	Fe_2O_3	SO_3	L.O.I.
1.70(0.69)	68.60(0.97)	17.00(0.57)	2.50(0.90)	0.80(0.04)	0.12(0.16)	1.78

Note: Values in parentheses are the standard deviation.

Table 1.
Chemical composition of CWP using XRF (modified from [43]).

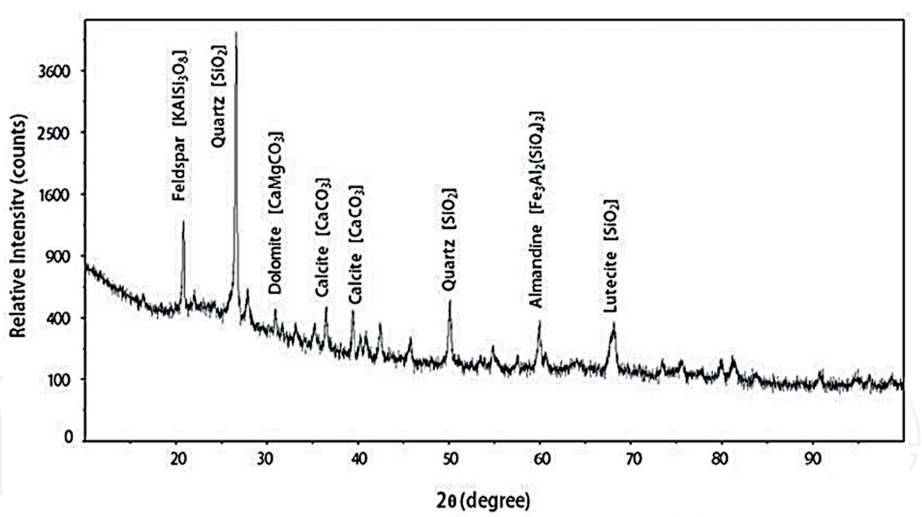


Figure 4.
XRD pattern of CWP [43]. Reproduced with permission from the publisher.

	CWP replacement level (mass %)			
	10%	20%	30%	40%
Average 28 days strength (MPa)	39.9	46.0	48.8	37.5
Standard deviation (MPa)	4.0	3.0	4.4	1.2
Strength activity index (SAI) in (%)	91.0	105.0	110.5	85.5

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Table 2.
Strength activity index (SAI) results for CWP [43].

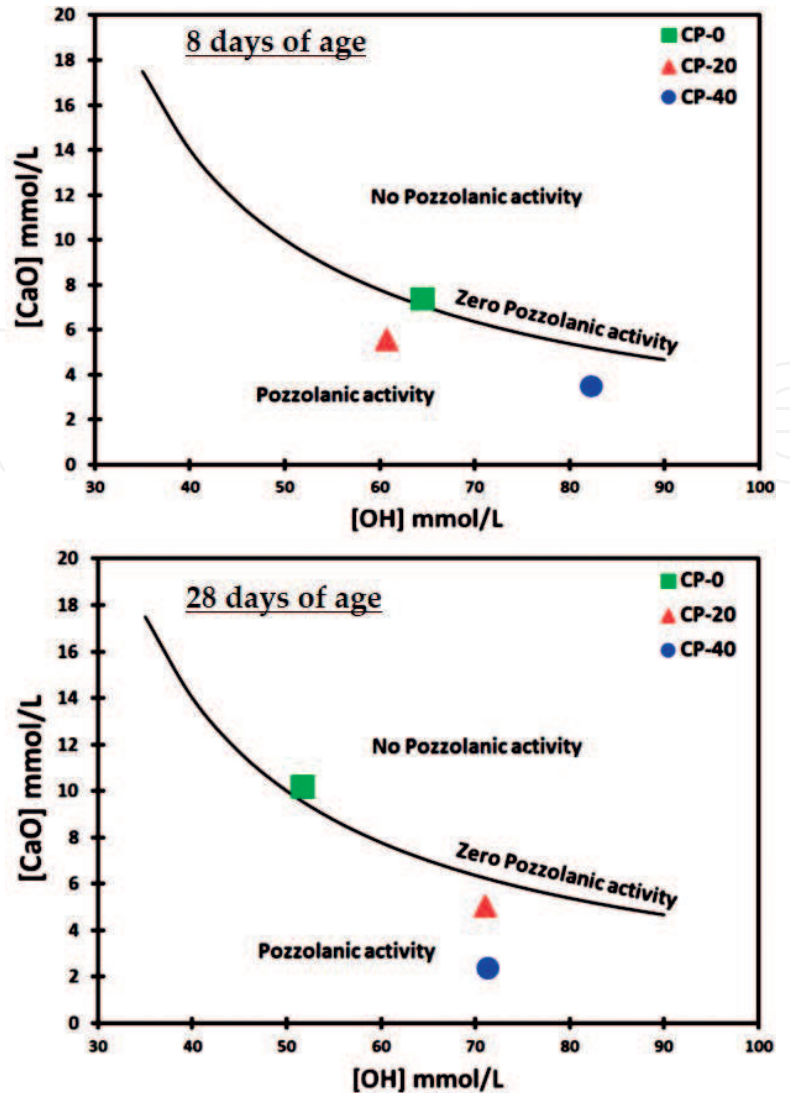

Figure 5.
Frattini test at 8 and 28 days of CP with CWP replacement [45]. Reproduced with permission from the publisher.

and 40% CWP replacement of Portland cement exhibited pozzolanic activity at 8 and 28 days age of concrete as shown in **Figure 5**.

In conclusion, CWP is silica and alumina rich material with some amorphous phases. The CWP has some pozzolanic activity, especially at a late age, as confirmed by strength activity index and Frattini tests. Therefore, CWP possesses the potentials to be used as a partial cement replacement in CVC and SCC mixtures, and as a main binder source to make AAC mixtures.

3. Conventional-vibrated concrete (CVC)

CWP is used to partially replace cement (0, 10, 20, 30 and 40% by weight) in different CVC mixtures. Two concrete grades with different cement contents are studied (25 and 50 MPa). The mixtures are chosen to cover several applications and different cement contents. All mixtures are designed to have a slump value from 60 to 100 mm. **Table 3** gives the mixtures' proportions of the mixtures. Initial slump values (i.e., ASTM C 143 [51]) is used to judge the mixtures' workability. The time to reach zero slump is used to assess the workability retention of the concrete mixtures. The development of compressive strength with age (i.e., 7, 28 and 90 days) and drying shrinkage (i.e., 120 days) are measured. Rapid chloride ion penetration

Mixture I.D.	Cement	CWP	Fine aggregate	Coarse aggregate	Water content	Initial slump (mm)
M25-0	310	0	749	1102	190	110
M25-10	279	31	737	1105	190	130
M25-20	248	62	734	1101	190	103
M25-30	217	93	731	1097	190	95
M25-40	186	124	629	1093	190	55
M50-0	485	0	662	993	208	55
M50-10	437	48	658	988	208	65
M50-20	388	97	654	981	208	60
M50-30	340	145	650	975	208	42
M50-40	291	194	673	968	208	10

Table 3.
Mixtures' proportions (kg/m^3) and initial slump values (mm) (modified from [43]).

test (RCPT) (i.e., ASTM C 1202 [52]) and bulk electrical resistivity test (i.e., ASTM C 1760 [53]) are conducted at 28 and 90 days of age to evaluate the durability of the concrete mixtures. Triplicate samples are used for the compressive strength, drying shrinkage, RCPT, bulk electrical resistivity and permeable pores tests and the average results are used. The development of the microstructure is assessed by measuring permeable pores (i.e., ASTM C642 [54]) and the pore system (i.e., total porosity and median pore diameter) is measured by mercury intrusion porosimetry (MIP). Both are measured at 90 days of age. Main microstructure characteristics are identified using scanning electron microscopy (SEM).

Concrete mixtures are prepared using ordinary Portland cement (OPC) as the primary binder. The specific surface area of cement is 380 m^2/kg. Natural crushed stone of maximum size 19.0 mm is used as coarse aggregate. The specific gravity is 2.65 while the absorption was 1%. Natural sand with fineness modulus between 2.5 and 2.7 is used as fine aggregate. The specific gravity is 2.63.

3.1 Workability and workability retention of fresh concrete

Initial slump values are given in **Table 3**. As CWP inclusion level increases, the initial slump value decreases as a result of its high specific surface area (SSA) compared to that of the cement (i.e., the SSA of CWP is 1.5 times that of the cement). Workability retention defines the time available for easy handling the mixture. **Figure 6** shows the time to zero slump of the concrete mixtures including CWP. It is noted that the workability retention time increases due to the inclusion of CWP. This could a result of CWP has no hydraulic reaction, and its pozzolanic reaction is slow. The use of 10% CWP in the 25 MPa mixtures has the highest workability retention. While for the 50 MPa mixtures, the use of 20% CWP shows the best retention time.

3.2 Compressive strength

The compressive strength development at different ages is shown in **Figure 7**. The coefficient of variation (COV) ranged from 0.4 to 4.8%. The compressive strength values at 7 and 28 days of age are lower than the target strength for both mixtures (i.e., 25 and 50 MPa). The reduction in strength is proportional to the CWP content.

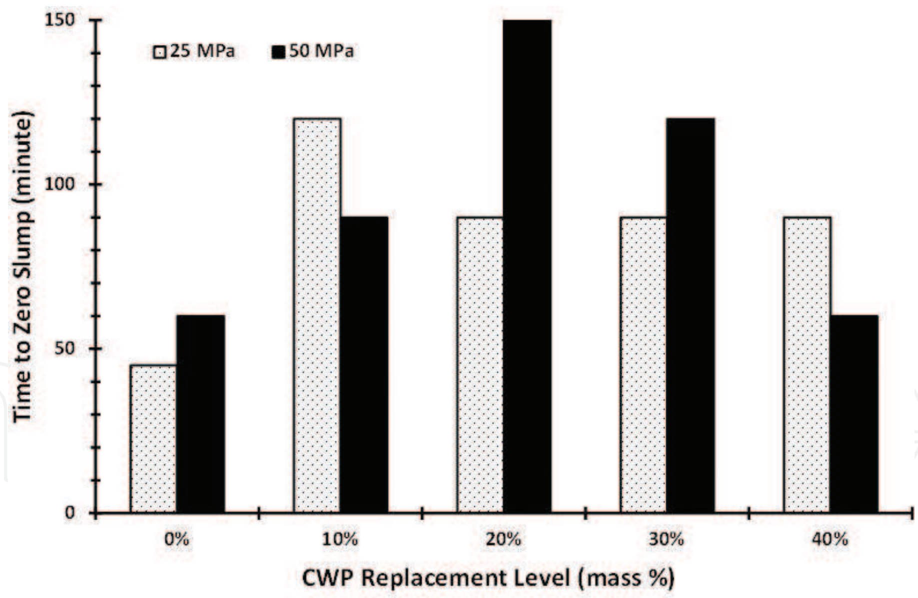

Figure 6.
Time to zero slump.

This could be attributed to the fact that CWP has no hydraulic reaction. Also, its contribution to early strength depended mainly on its microfilling ability (i.e., CWP particles' size ranged from 5 to 10 μm). This behavior agrees with that of most pozzolanic materials with slow strength development at early ages [55]. Also, slowed strength development at early ages is reported for CWP [28–30, 32].

At a late age (i.e., 90 days) all the 25 MPa mixtures including CWP achieve compressive strength values higher than the target strength. The mixture with 10% CWP shows the highest compressive strength. The strength gain at 90 days of age might be due to the pozzolanic characteristics of the CWP material. For the 50 MPa mixtures, all CWP mixtures the target strength is achieved. The increase in strength values could be justified by the delayed pozzolanic reaction of the CWP. The CWP particles could have worked as nucleation sites for cement grains and hydration products which led to a denser microstructure.

3.3 Drying shrinkage

Table 4 shows the 120 days drying shrinkage strain values. The COV ranged from 20 to 26%. It is observed that the drying shrinkage strain decreases with increasing the CWP replacement level. The pores' structure and connectivity of pores are changed due to the fine CWP particles and its pozzolanic action. This change results in restricting water movement through the concrete. The drying shrinkage values for mixtures including 10 and 20% CWP do not differ significantly from that of the control mixtures. For the 25 MPa mixtures, CWP with replacement levels of more than 20% reduces the drying shrinkage strain between 29 and 60% compared to the control mixture. While for the 50 MPa mixtures a decrease in the drying shrinkage strain values between 28 and 53% for CWP replacement levels above 20% are observed.

3.4 Chloride ion penetration test (RCPT)

The concrete durability concerning its resistance to chloride ion penetration and chloride induced corrosion can be judged by the RCPT. The inclusion of CWP as partial cement replacement has a significant effect on the chloride ion penetration

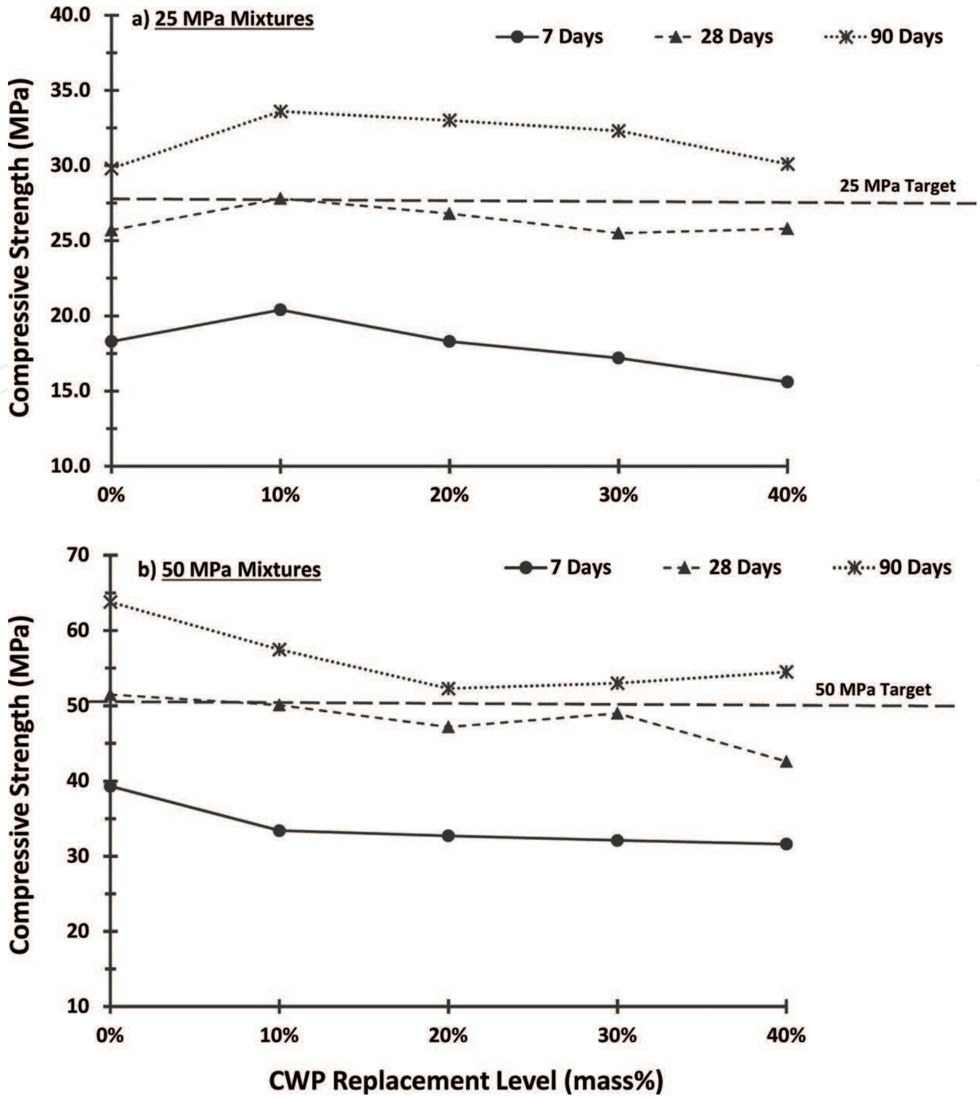

Figure 7.
Compressive strength development with age.

Mixture	Shrinkage strain (microstrain)	Mixture	Shrinkage strain (microstrain)
M25-0	2608	M50-0	2569
M25-10	2488	M50-10	2222
M25-20	2817	M50-20	2413
M25-30	1033	M50-30	1199
M25-40	1859	M50-40	1848

Table 4.
Drying shrinkage strain values at 120 days (microstrain) (modified from [43]).

of the 25 and 50 MPa concrete mixtures. **Figure 8** demonstrates a significant reduction in the 28 and 90 days' test results of all CWP concrete mixtures. The COV ranged from 3 to 15%.

At 28 days of age, the use of 20, 30 and 40% CWP reduces the total passed charge by 2–8 times lower than that of the control mixture. Mixtures with 30 and 40% are rated as "Very Low" for chloride ion penetration as per the classification of the ASTM C1202 [52]. At 90 days of age, the chloride ion penetration classification of all the 25 MPa mixtures including CWP is "Very low." The reduction in the total

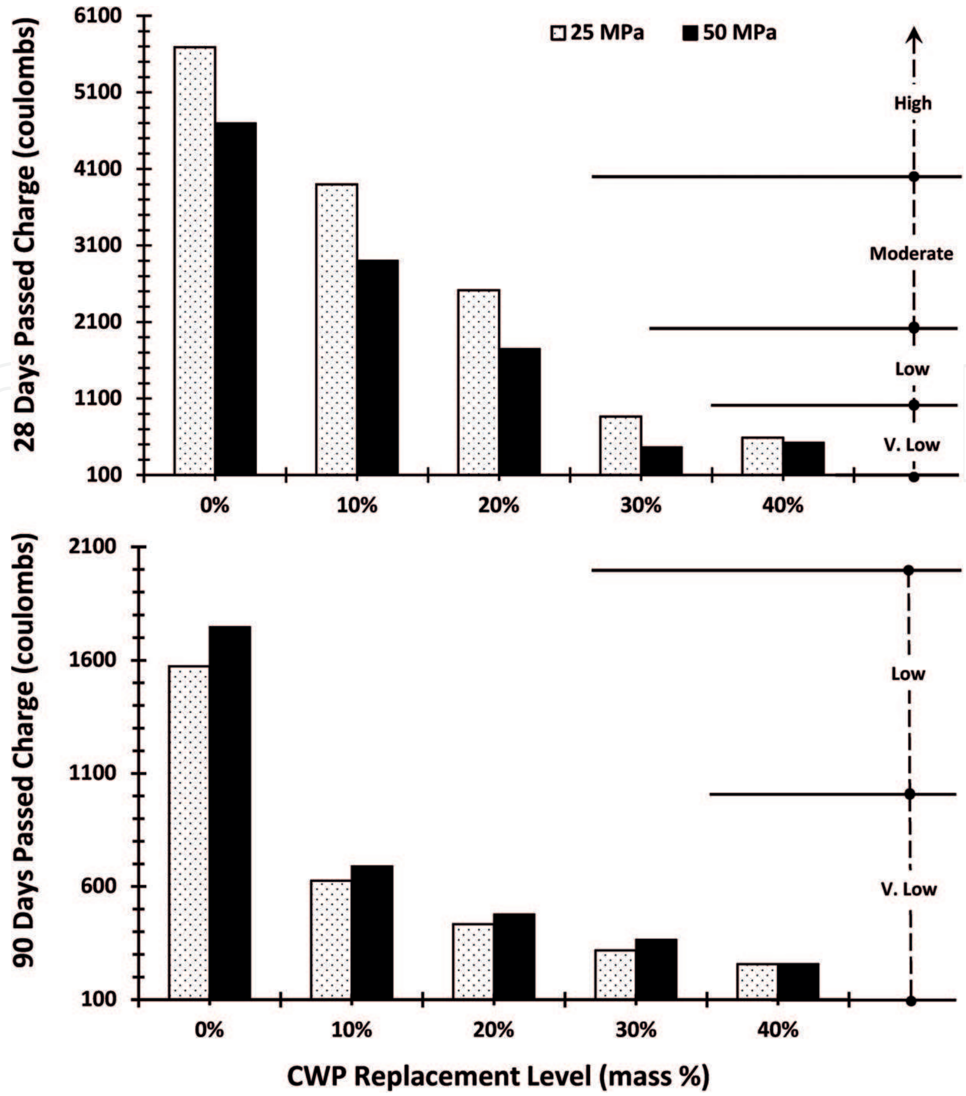

Figure 8.
Chloride ion penetration.

passed charge for the mixtures incorporating CWP compared to its corresponding 28 days values ranged from 56 to 84%.

While for the 50 MPa mixtures, the 28 days chloride ion penetration decreases with the inclusion of CWP. The reduction is proportional to the CWP content. The reduction with respect to the control mixture is 38% for the use of 10% CWP and 90% for the use of 40% CWP. The ASTM classification of mixtures including high levels of CWP (i.e., ≥20) is shifted from "High" to "Low" and even "Very Low." At the 90 days of age, chloride ion penetration for all 50 MPa CWP mixtures is classified as "Very Low." This significant reduction could be due to the microstructure densification and refinement of the pore structure provided by the fine particles of CWP in addition to its pozzolanic effect. Also, the reduction with age indicates the development of a dense microstructure, especially with discontinuous pore system. Similar findings were reported in other studies [6, 30, 34, 56].

3.5 Bulk electrical resistivity test

The corrosion protection of the concrete to the embedded reinforcement can be assessed by its electrical resistivity [57]. **Figure 9** displays the bulk electrical resistivity at 28 and 90 days of age. The COV ranged from 4 to 10%. It should be noted that electrical resistivity is mainly affected by the porosity and the pore size distribution [58]. Therefore, the development of the microstructure could be judged by measuring the electrical resistivity. Ionic mobility is reduced by the discontinuity of pores, and hence concrete resistivity and corrosion protection will increase. The resistivity results of all concrete mixtures including CWP are higher than those of the control mixtures. Microfilling effect and pozzolanic activity of the CWP which could lead to a denser microstructure could be the main reasons for the increase in the resistivity of the mixtures including CWP. It was reported that the use of ceramic polishing residues was reported to reduce water permeability of cement mortar samples [6, 34].

At 28 days of age, 25 MPa mixtures including 20, 30 and 40% CWP have a resistivity higher than 10 kΩ.cm. This is classified as "High" to "Very High" corrosion protection levels according to ACI 222R-01 [57]. The increase in resistivity is proportional to the CWP replacement level. At 90 days of age, using CWP demonstrates a significant increase in the electrical resistivity values with respect to the

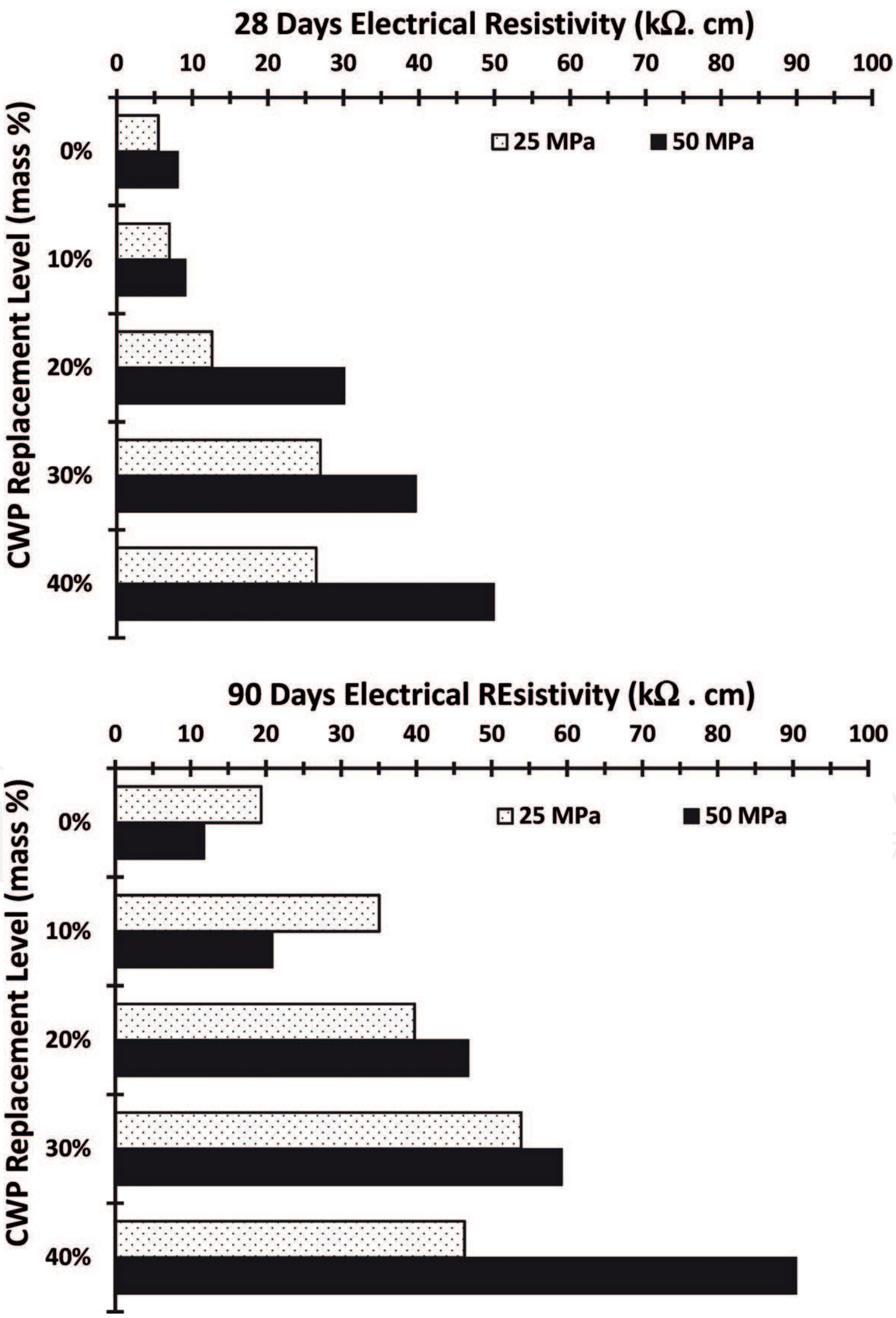

Figure 9.
Bulk electrical resistivity.

control mixture. The 50 MPa concrete mixtures with CWP had similar performance to the 25 MPa mixtures at both ages. Including 10% CWP results in a "High" corrosion protection level. When CWP is included with 20% or more the corrosion protection level is "Very High" at both ages.

Both RCPT and resistivity results confirm the performance of the concrete mixtures including CWP with regards to chloride ion attack, chloride-induced corrosion, and corrosion protection.

3.6 Permeable pores

The permeable pores of the concrete mixtures can assess the development of the pore system and judge the microstructure development. **Figure 10** shows the permeable pores measured at 90 days of age. The COV ranged from 2 to 8%. In general, the permeable pores are decreased by the inclusion of CWP compared to the control mixture.

In the case of the 25 MPa mixtures, the permeable pores are reduced by 17% up to 36% due to the inclusion of CWP as a partial cement replacement. Similar performance is observed for the 50 MPa mixtures. The reduction in pores volume ranged from 2 to 24% compared to the control mixture. The inclusion of the fine CWP particles with high SSA could physically have a microfilling effect and improves the particles' packing in the mixtures. Also, to the CWP pozzolanic activity, the mixtures microstructure is densified. Therefore, the pore structure is refined resulting in lower pore volume. The reduction in permeable pores reduces the mobility of water from inside the concrete which is reflected in reducing the reduction in the drying shrinkage strain. Also, reduction in chloride ion penetration and immobility of ions are direct effects of the pores' size refinement. This is reflected in the reduction of the chloride ions penetration and the improvement of the electrical resistivity with age.

3.7 Mercury intrusion porosimetry (MIP)

MIP is a widely used test to characterize the pore structure of cement-based materials. The test is capable of providing information about the total porosity, and

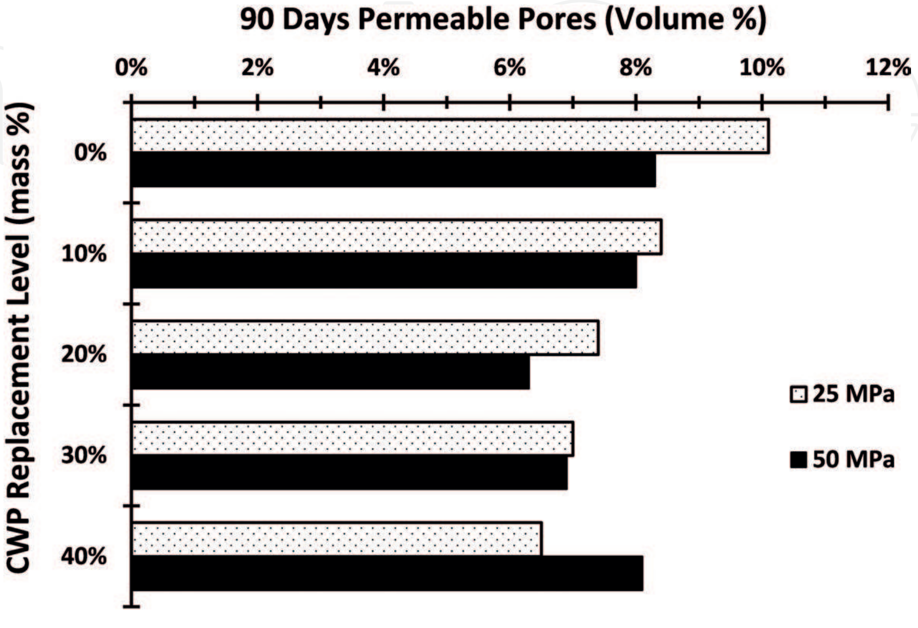

Figure 10.
Ninety days permeable pores.

the median pore diameter based on intruded volume. The concrete pore system indicates its microstructural development that can be related to its performance.

Table 5 gives the results of the MIP test regarding total porosity percentage and the median pore diameter based on intruded volume at 90 days of age. The inclusion of CWP reduces the total porosity at 90 days of age. The use of 40% CWP as partial replacement of the cement reduces the porosity by 9 and 19% for the 25 and 50 MPa mixtures respectively compared to the same mixtures without CWP. The median pore diameter is reduced due to the inclusion of CWP. It is noted that the reduction was proportional to the CWP content. The reduction in the total porosity and the median pore diameter confirms the densification of the microstructure due to the inclusion of CWP as a partial cement replacement.

The reduction in the total porosity and especially the reduction in the pore size confirm the superior durability performance of the mixture observed at the late age. The microstructure development could be related to the durability performance. The median pore diameter was correlated to the 90 days RCPT and electrical resistivity values as shown in **Figure 11**. The median pore diameter correlates well with the durability test results. The correlation coefficient (R^2) is 0.9517 and 0.7977 for the median pore diameter relationship with the RCPT and the electrical resistivity respectively.

3.8 Microstructure characteristics

To better understand the performance of CVC mixtures including CWP, the main microstructural characteristics are inspected by scanning electron microscope (SEM). Microstructure examination is conducted at 90 days of age. The examination is conducted on the control mixture for both concrete grades (i.e., M25-0 and M50-0), and the mixtures including the highest CWP content (i.e., M25-40 and M50-40).

Figure 12 shows the SEM images of the general characteristics for M25-0 and M25-40. For the M25-0 mixture, crystalline hydration products are observed in addition to several pores. For M25-40, fewer pores with smaller size are noticed which indicates the densification of the microstructure that confirms the superior durability performance. Few crystalline hydration products are observed. **Figure 13** displays the aggregate matrix interfacial transition zone (ITZ) for M25-0 and M25-40

Mixture	Porosity (%)	Median pore diameter* (μm)
M25-0	21.297	4.2586
M25-10	20.015	4.0115
M25-20	19.754	3.7404
M25-30	19.135	3.6184
M25-40	19.437	3.4737
M50-0	22.426	4.0380
M50-10	21.131	3.8382
M50-20	19.415	3.5876
M50-30	18.944	3.5747
M50-40	18.126	3.4000

**Based on the intruded volume.*

Table 5.
MIP results at 90 days of age.

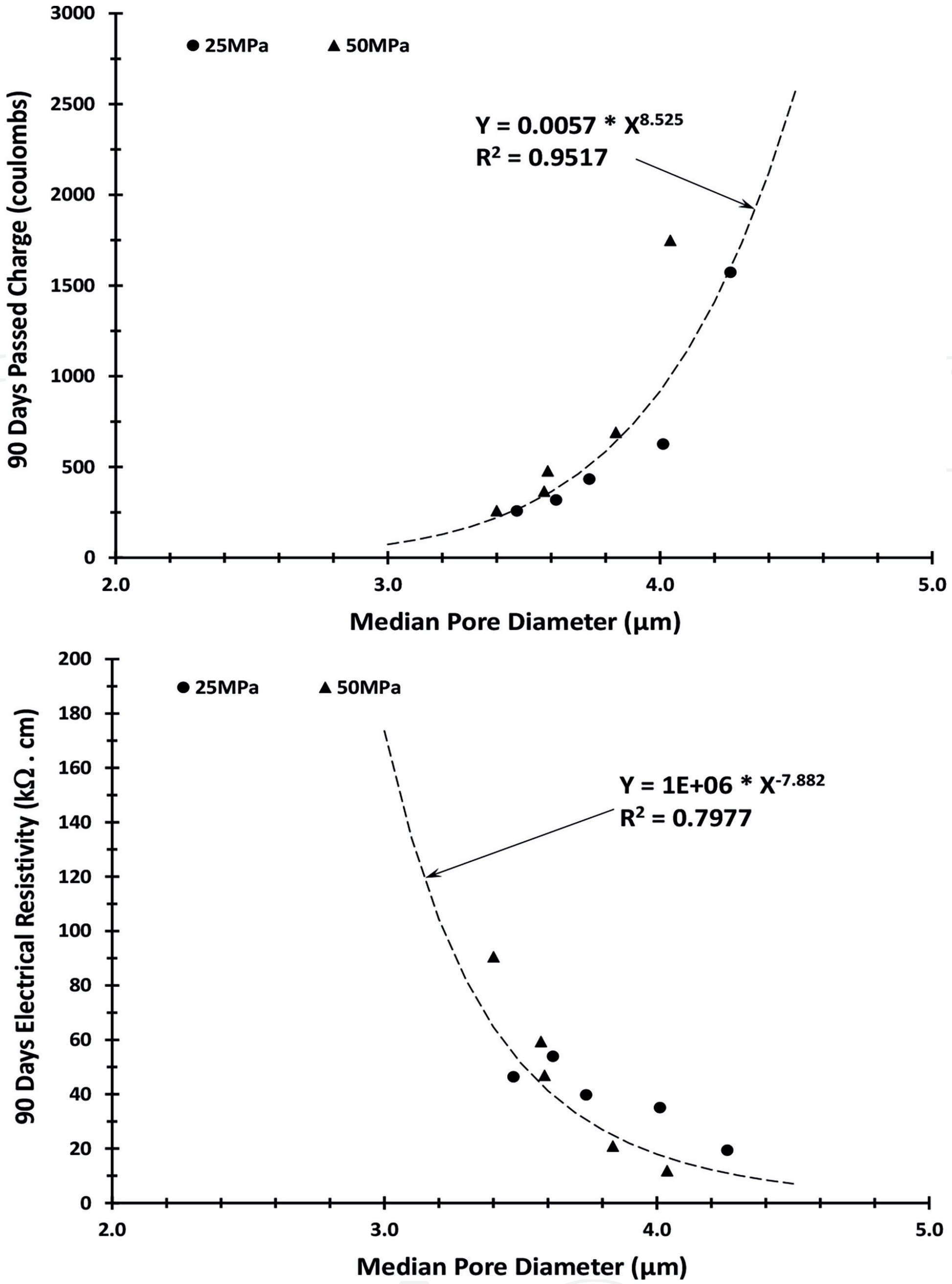

Figure 11.
Relation between median pore diameter and 90 days RCPT and electrical resistivity.

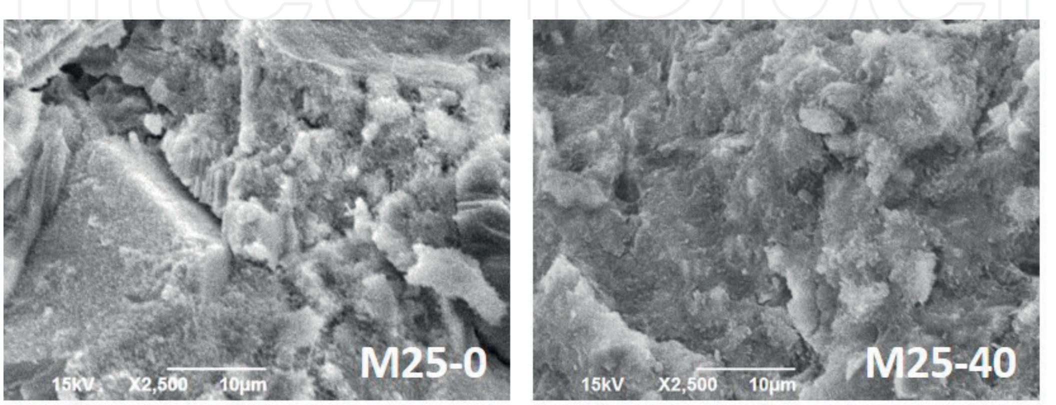

Figure 12.
SEM image of general microstructure for M25-0 and M25-40 mixtures.

mixtures. Crystalline hydration products are noticed in both mixtures in the ITZ region with smaller crystal size in M25-40 mixture. The matrix around the aggregate in the M25-40 mixture includes lesser pores compared to M25-0, this is similar to the observations of the general matrix microstructure.

The general microstructure for M50-0 and M50-40 is shown in **Figure 14**. Generally, the 50 MPa mixtures have a denser microstructure compared to the 25 MPa mixtures. For the M50-0 mixture, few pores are noticed, and the crystalline hydration products are smaller in size. The inclusion of CWP densified the microstructure by refining the pore structure as depicted in the SEM image. The ITZ region microstructure is presented in **Figure 15**. The incorporation of CWP improves the densification of the ITZ region microstructure. The crystalline hydration products and pores' size are reduced due to the inclusion of CWP.

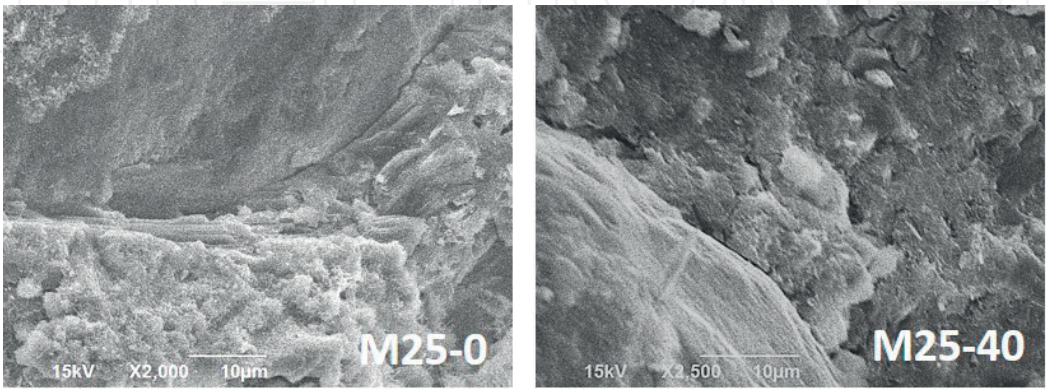

Figure 13.
SEM image of ITZ region for M25-0 and M25-40 mixtures.

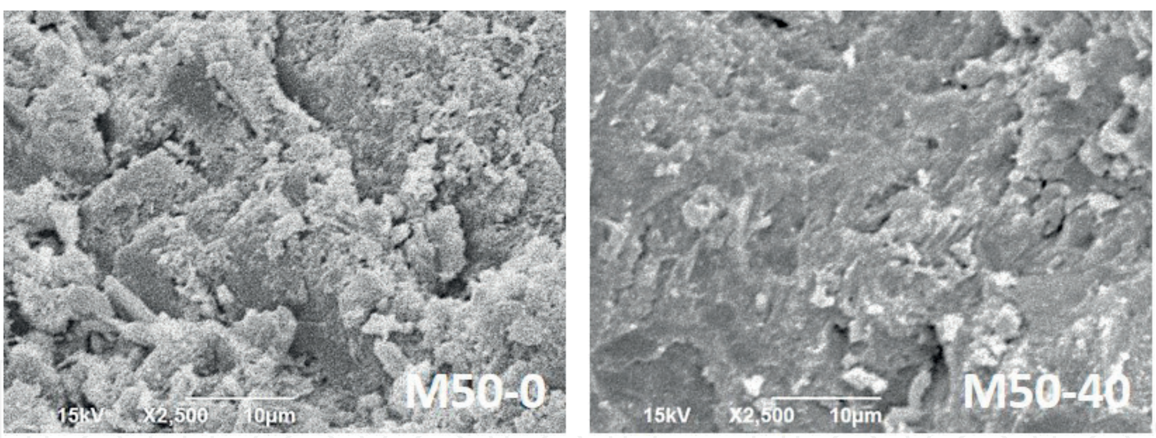

Figure 14.
SEM image of general microstructure for M50-0 and M50-40 mixtures.

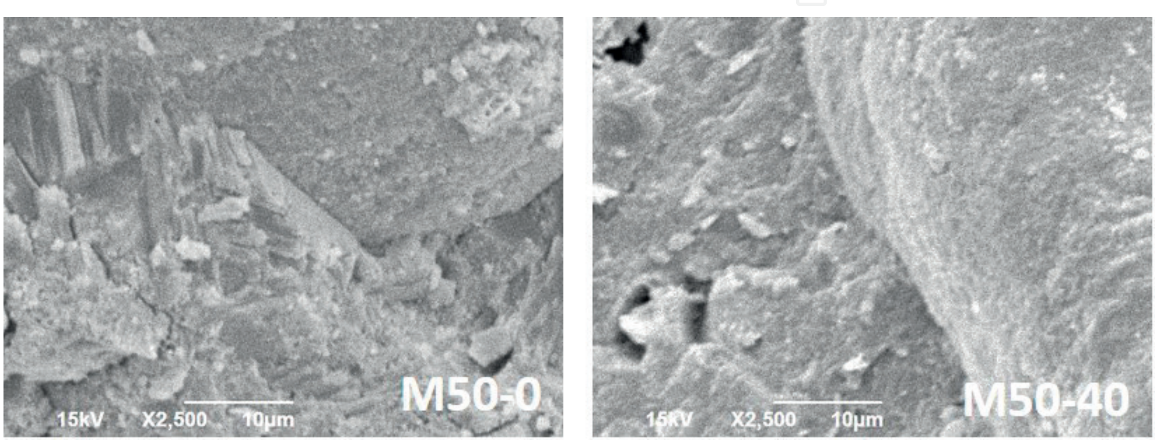

Figure 15.
SEM image of ITZ region for M50-0 and M50-40 mixtures.

4. Self-compacting concrete (SCC)

Self-compacting concrete (SCC) has received wide attention and used in the construction industry worldwide since its development [59]. SCC is featured with high fluidity, and at the same time, high resistance to segregation and is placed purely under its weight without the need for vibration [60–62]. SCC properties are the result of modifying the composition of CVC by incorporating high powder content that has been mainly cement. However, the use of high cement content is not desirable as it will increase the cost and has other negative environmental effects. Replacing cement in SCC mixtures with waste powder is a trend gaining a great deal of attention with the growing awareness toward environmental protection and sustainable construction [63–70]. CWP is used to partially replace cement to produce eco-friendly SCC. The cement content in the control mixture is 500 kg/m^3 based on the preliminary mix design. The powder content of the control mixture meets the recommended value by EFNARC specifications [71]. The cement is partially replaced by the CWP in 20, 40 and 60% by weight. The concrete mixture is expected to yield compressive strength in the range of 80 MPa. The details of the mixtures' proportions are given in **Table 6**.

Ordinary Portland cement (OPC) is used as the main binder. The specific surface area of cement is 380 m^2/kg. Natural crushed stone of maximum size 9.5 mm is used as coarse aggregate. The specific gravity is 2.65 while the absorption was 0.7%. Natural sand with fineness modulus between 2.5 and 2.7 is used as fine aggregate. The specific gravity is 2.63.

Several tests are conducted to investigate the effect of replacing cement with CWP on the fresh properties of the produced concrete. Unconfined flowability of the produced SCC mixture is assessed by the slump flow test in accordance to ASTM C1611 [72]. Passing ability is evaluated through two tests namely the J-ring (i.e., ASTM C1621 [73]), and L-box. The segregation resistance is measured through conducting the GTM segregation column test conforming to ASTM C1610 [74]. Finally, the viscosity is measured by following the V-funnel test procedure described in the EFNARC specification [71]. On the other hand, compressive strength is performed at two test ages (i.e., 7 and 28 days) in order to evaluate the strength development. The durability characteristic is evaluated by conducting the bulk electrical resistivity as per ASTM C1760 [53] at 28 and 90 days of age. Triplicate samples are used to

Mixture ingredients	Mixture designation			
	Control	R-20	R-40	R-60
Cement	500	400	300	200
CWP	0	100	200	300
Water	175	175	175	175
Fine aggregate	871	871	871	871
Coarse aggregate	871	871	871	871
Super plasticizer	8.33	8.72	8.33	8.80
VMA*	1.6	1.6	1.6	1.6
w/cm**	0.35	0.35	0.35	0.35

**VMA = viscosity-modifying admixture.*
***w/cm = water/(cement + slag or CWP).*

Table 6.
Mixtures' proportions for SCC (kg/m^3).

conduct the compressive strength and the bulk electrical resistivity tests and the average results are used. **Figure 16** shows the different tests conducted. The microstructure development is judged by measuring the permeable pore volume at 28 and 90 days of age. Also, the pore system (i.e., total porosity and median pore diameter) is assessed using mercury intrusion porosimetry (MIP). The MIP is conducted at 90 days of age.

4.1 Slump flow results

Slump flow test evaluated the unconfined flowability of the produced SCC mixtures. **Figure 17** displays the test results together with the EFNARC specifications [71].

It is noticed that the slump flow decreases as the amount of CWP in the mixture increases. Even with the reduction in the slump flow values, none of the CWP

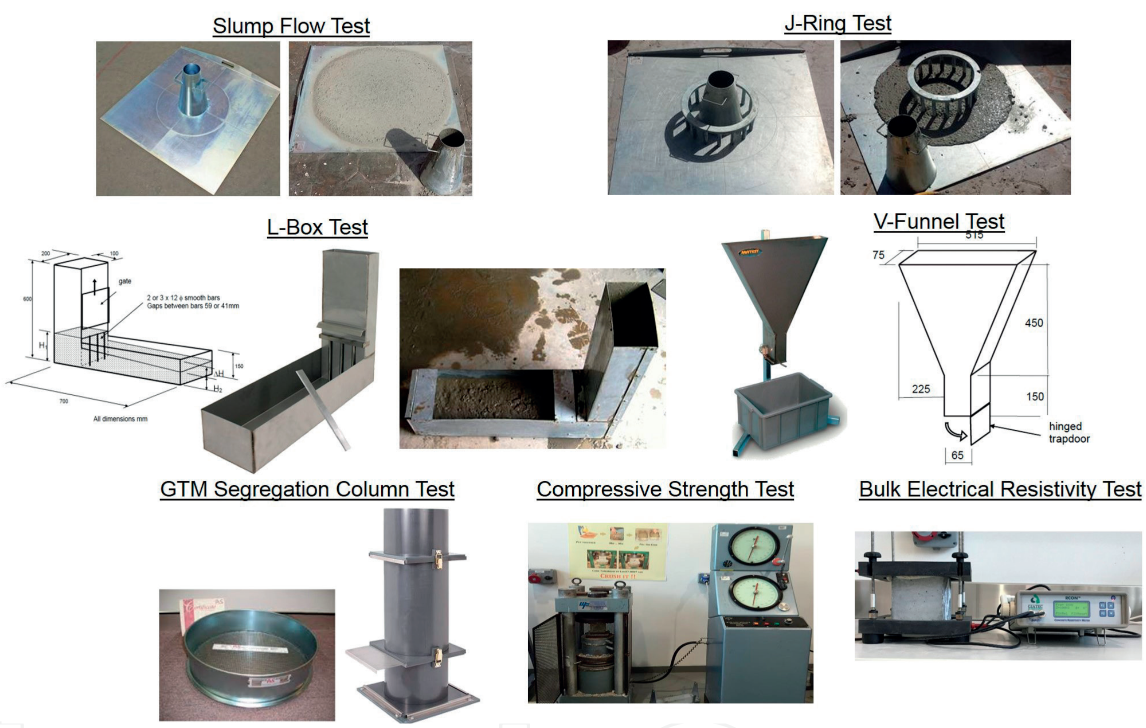

Figure 16.
Different tests conducted on SCC.

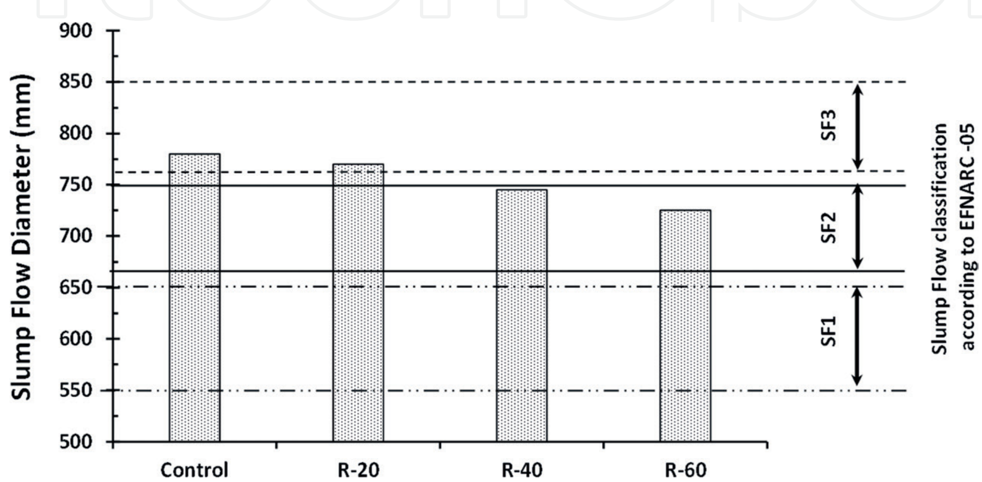

Figure 17.
Slump flow results.

mixtures dropped to the slump flow class one (SF1) which is critical in the presence of highly congested reinforced concrete structures.

Chopra and Siddique [48] reported a similar trend when using rice husk ash (RHA) as cement replacement. The relatively higher specific surface area (SSA) of the CWP compared with cement would increase the water demand and accordingly resulted in lower slump flow values. Similarly, Sfikas et al. [75] reported a reduction in the slump flow of SCC when they used metakaolin, which is characterized by a high SSA, to replace cement.

The time taken for concrete to reach the 500 mm diameter circle on the steel base plate of the slump flow test is measured (T50). The T50 value can judge the viscosity of the SCC mixtures. High T50 values indicate mixtures with higher viscosity. The T50 results are given in **Table 7**.

4.2 J-ring results

The passing ability of SCC is evaluated by the J-ring test. This test evaluates how the SCC mixtures can perform in the presence of reinforcing bars in form works. The difference between the unrestricted slump flow diameter and the J-ring flow diameter is shown in **Figure 18**. The inclusion of CWP improves the passing ability of the SCC mixtures. As the CWP content increases the mixtures' passing ability is improved and shows a great capacity for flowing through congested spaces. Therefore, mixtures containing high CWP perform better than the control mixture with regards to the passing ability.

4.3 L-box results

The passing ability of SCC through congested reinforcement can also be assessed by using the L-box test. The L-box results are given in **Table 7**. Comparable blocking ratios are observed for all tested mixtures. The variation is less than 1.5%. SCC mixtures including CWP mixtures show no signs of blocking. Generally, EFNARC [71] suggests blocking risk is likely if the blocking ratio is below 0.8. The viscosity of the mixtures is too high if the blocking ratio is less than 0.8. This can cause blocking around highly congested sections. Based on the results, all mixtures with CWP can be used in applications where flow through congested reinforcement is needed.

4.4 V-funnel results

In this test, the viscosity and filling ability of the fresh concrete is judged by the V-funnel test where the concrete is forced to flow through small cross sections and confined spaces. The flow rate (i.e., V-funnel time) of the SCC through the small cross-section is directly related to the mixture's viscosity.

The V-funnel test results are given in **Table 7**. The V-funnel results show an increasing trend, indicating a higher viscosity of the mixtures. All the measured

Property measured	Control	R-20	R-40	R-60
T50 (seconds)	2.68	2.47	3.24	4.04
V-Funnel (seconds)	10.4	10.01	11	12.82
L-box ratio (H2/H1)	0.963	0.966	0.977	0.967

Table 7.
Fresh test results (modified from [42]).

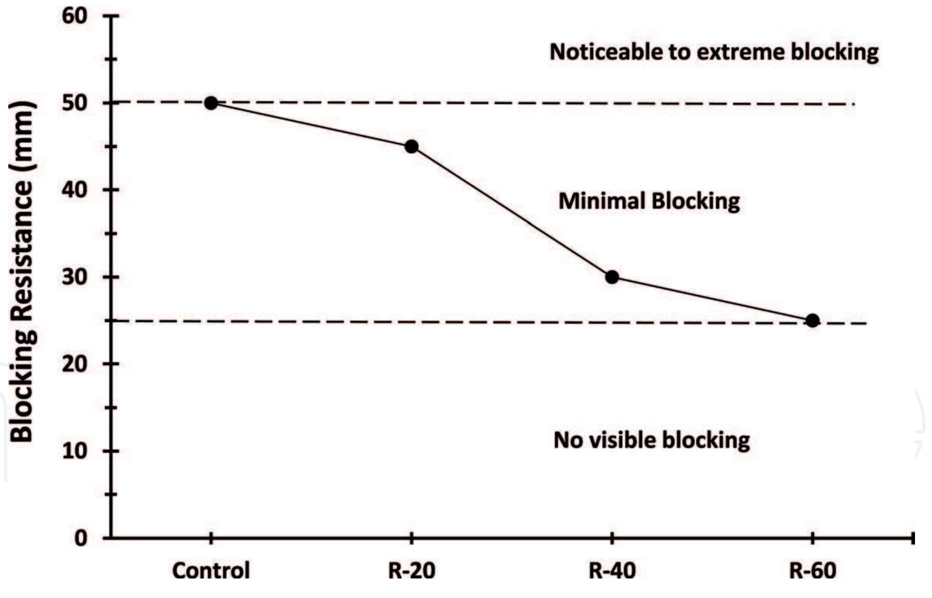

Figure 18.
J-ring results.

V-funnel time values correspond to the second viscosity class according to EFNARC specification [71]. The increase in the viscosity indicates an improvement in the segregation resistance. The viscosity-modifying admixture (VMA) is typically used to adjust mixtures' viscosity and enhance segregation resistance. Since the mixtures' viscosity values are significantly enhanced by the incorporation of CWP the VMA could be eliminated from the mixture or its dosage could be reduced. This would result in more economical and low-cost mixtures.

4.5 GTM segregation column results

The ability of concrete to remain homogeneous in the composition in its fresh state is defined as its segregation resistance. The GTM segregation column test is used to evaluate the mixtures' segregation resistance.

Segregation percentage is shown in **Figure 19**. The segregation percentage decreases as the CWP content increases in the mixtures. The CWP significantly improves the segregation resistance of the SCC mixtures. The incorporation of CWP in SCC enhances the cohesiveness characteristics of the mixtures. The segregation percentages are below 15%, which shows that the SCC mixtures were superior regarding segregation resistance. Segregation resistance is related to viscosity. The improvement in segregation resistance is confirmed by the V-funnel test results. As the amount of CWP increases in the mixtures from 0 to 60%, the segregation resistance is enhanced by 72.5%. The substantial enhancement in the segregation resistance can be explained by the fact that the water adsorption of the CWP particles may induce suction forces possibly leading to cluster formation. This will lead to an increase in the inter-particle bonds as in the clustering theory enhancing the segregation resistance similar to RHA mixtures studied by Le and Ludwig [76].

4.6 Compressive strength results

Strength is measured at different test ages (7, 28, and 90 days) to evaluate the strength development as affected by the inclusion of CWP as partial cement replacement. The strength development due to the inclusion of any cement replacing material is mainly affected by the cement hydration and pozzolanic reaction the used material, and the effect on the concrete microstructure especially the densification of the microstructure with a particular focus on the aggregate-paste interfacial zone [77].

Figure 20 shows the compressive strength development with age. The COV ranged from 0.4 to 3.0%. At the 7 days of age, it is noticed that the inclusion of CWP decreases the strength and the reduction is proportional to the CWP content. This could be a direct result of replacing cement by CWP which has no hydraulic reaction. At the 28 days of age, the mixture including 20% by weight CWP showed higher strength compared to the control mixture. Nevertheless, the mixture of 60% by weight CWP shows the least developed strength. Since CWP is characterized by the slow pozzolanic reaction, it is expected not to see much effect until late ages. At the 90 days of age, the improvement in strength is noticeable. At the 90 days of age, mixtures with 20 and 40% by weight CWP achieve the highest compressive strength compared to the control mixture. This implies that 20–40% by weight CWP is the optimum cement replacement to obtain high compressive strength.

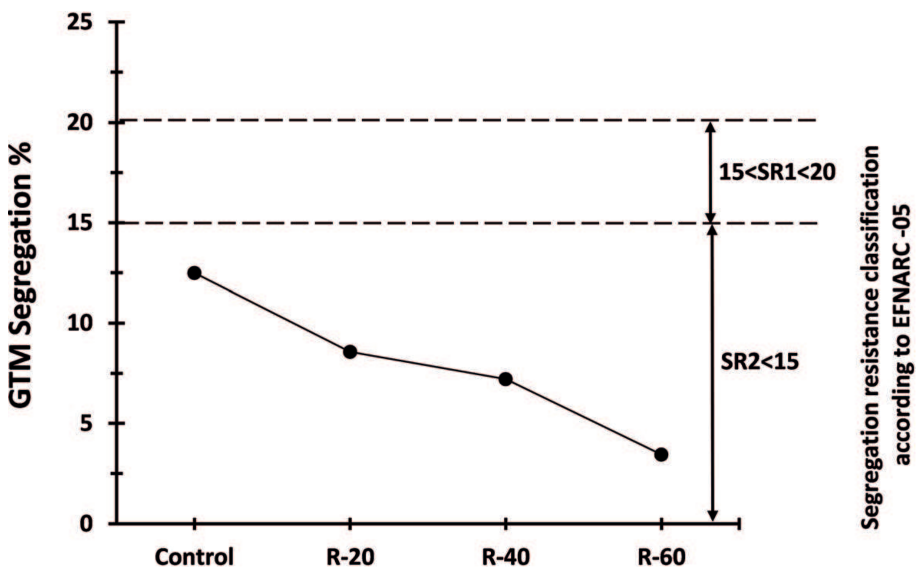

Figure 19.
Segregation resistance results.

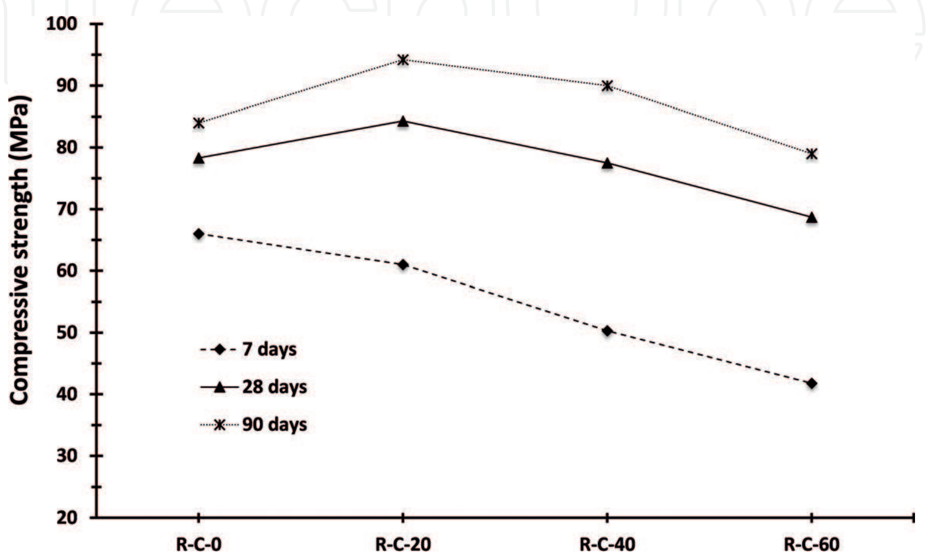

Figure 20.
Compressive strength development with age.

The increase in the strength can also be explained through the nucleation sites (i.e., nucleation of CH around the CWP particles). The CWP improves the packing of the concrete mixture due to its high SSA and its pozzolanic reaction, and the cement hydration acceleration similar to the effect of rice husk ash (RHA) observed in another investigation [76]. On the other hand, the use of 60% by weight CWP shows marginal improvement in strength; this can be due to the high amount of silica from the CWP, and the insufficient amount of calcium hydroxide (CH) from the cement hydration. Hence, some silica is left without chemical reaction. Similar behavior was observed by using RHA (i.e., characterized by high SSA and high silica content) as cement replacement [48].

4.7 Bulk electrical resistivity results

The electrical resistivity of concrete is affected by several factors such as porosity, pore size distribution, connectivity, concrete's moisture content, and ionic mobility in pore solution. Electrical resistivity assesses the concrete protection of reinforcing steel against corrosion. According to ACI 222R-01 [57], the corrosion protection level is improved as the resistivity value increases.

The resistivity values are presented in **Figure 21** at 28 and 90 days of age. The COV ranged from 6.4 to 13.2%. The resistivity increases with age. The inclusion of CWP significantly increases the mixtures' resistivity. The significant increase in the resistivity due to the inclusion of CWP suggests that CWP tended to reduce the interconnected pore network contributing to the reduction of the concrete's conductivity. With age, CWP pozzolanic activity contributes to the refinement of concrete pores and microstructure, thus further reduces the ionic mobility and hence the concrete's conductivity. The improved resistivity indicated that the durability of the CWP concrete mixtures to protect reinforcing steel against the corrosive environment is much better than that of the control mixture without CWP.

4.8 Mercury intrusion porosimetry (MIP)

The MIP test provides information about the pore system (i.e., pore volume and median pore diameter). The MIP results can help understand the development

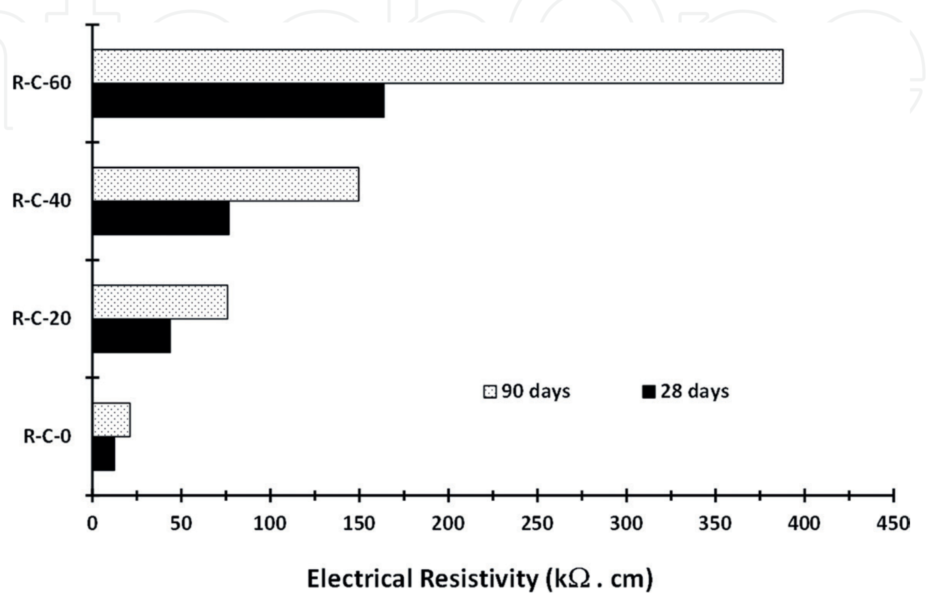

Figure 21.
Electrical resistivity of SCC.

Mixture	Porosity (%)	Median pore diameter* (μm)
R-C-0	24.989	8.1265
R-C-20	17.737	5.3136
R-C-40	15.604	3.9109
R-C-60	13.304	2.5002

*Based on the intruded volume.

Table 8.
MIP results at 90 days of age (modified from [42]).

of the concrete microstructure and can also explain the other obtained results. **Table 8** shows the MIP test results at 90 days of age. Test results show that high CWP content has a significant reduction of the pore volume and the pores' size. The reduction in the pore volume and the pores' size indicates densification of the microstructure. Also, the MIP results confirm the improvement observed in the resistivity results and compressive strength.

5. Zero-cement alkali activated concrete (AAC)

Zero-cement alkali-activated concrete (AAC) emerged as an alternative to cement-based concrete [78–84]. Sometimes, AAC is referred to as inorganic-polymer or geopolymer concrete. In AAC, cement is completely replaced. AAC utilizes and silica and alumina rich materials to be alkali-activated to form a three-dimensional CaO-free alumino-silicate binder. AAC offers a significant opportunity for the reuse of several industrial by-products and wastes such as fly ash, metakaolin, and blast-furnace slag. Geopolymerization technology is based on the reaction of alkaline solutions such as sodium hydroxide (NaOH), potassium hydroxide (KOH) and sodium silicate solution. The CWP is characterized by its high silica and alumina content which makes it a good candidate to be used in making ACC. The limited studies on suing CWP in AAC [38–40] concluded that the optimum curing temperature ranges from 60 to 80°C, the curing period ranges between 24 and 48 hours, and the molarity of the alkali solution is 12 M.

The use of CWP in the making AAC still needs further investigations to develop a better understanding of its performance. CWP is used to make AAC using different alkali solutions, mainly NaOH and KOH. Several parameters are investigated which include alkaline solutions with 12 M concentration (i.e., NaOH alone, KOH alone and combination), CWP to aggregate ratio (i.e., 1:1.5–1:2.0–1:2.5), admixture dosage (i.e., 1.5 and 4.0%), curing time (i.e., 60°C for 24 and 48 hours), the inclusion of slag in addition to CWP (i.e., slag content 10, 20 and 40%). Several tests are used to evaluate the performance of the mixtures which include flowability (i.e., ASTM C1437 [85]), cube compressive strength, permeable pores (i.e., ASTM C642 [54]), initial rate of water absorption (i.e., ASTM C1585 [86]), and electrical resistivity (i.e., ASTM C1760 [53]). The COV ranged from 0.3 to 2.8%.

The sodium hydroxide flakes and potassium hydroxide are dissolved in distilled water to make a solution with the desired concentration (i.e., 12 M) at least 1 day before its use. **Table 9** shows the alkali solutions used and the combination of NaOH and KOH solutions. The dry ingredients are first mixed for about 1 minute. The sodium hydroxide and potassium hydroxide solutions are added to the dry materials based on the order of mixing in **Table 9** and mixed for 3 minutes.

I.D.	Alkali solutions %		Mixing regime of the solutions with the CWP
	KOH	NaOH	
A	0	100	—
B	100	0	—
C	20	80	NaOH solution is added first and mixed with solids for 1 minute, then KOH is added and mixing continues for an additional 2 minutes
D	40	60	NaOH and KOH solutions are mixed then added to solids and mixed for 3 minutes
E	60	40	KOH solution is added first and mixed with solids for 1 minute, then NaOH is added and mixing continues for an additional 2 minutes

Table 9.
Mixtures' I.D., alkali solutions used and mixing regime of solutions.

5.1 Effect of aggregate content

The effect of aggregate content was evaluated by the flowability and 7 days compressive strength. Mixtures are cured at 60°C for 24 hours. **Figure 22** shows the flowability and 7 days compressive strength as affected by the CWP to aggregate ratio. It is noticed that the flowability decreases as the aggregate content increases. This is similar to the behavior cement concrete as the CWP content acts as a lubricant between aggregate particles. Oppositely the 7 days compressive strength improved by the increase of the aggregate content. The mixing regime of the solution affects the flowability and strength. The mixing regime (A) shows the best flowability performance while the other mixing regimes show similar flowability values. The mixing regimes (D) and (E) produce the highest compressive.

5.2 Effect of admixture content

Superplasticizer (i.e., polycarboxylic ether based) is added with a dosage of 1.5 and 4.0% of the CWP weight. The AAC mixture with CWP to the aggregate ratio (1:2.5) and 24 hours curing at 60°C is used to examine the effect of admixture dosage. Flowability and the 7 days compressive strength results are presented in **Table 10**. The use of 1.5% by weight superplasticizer, shows variable improvement in the flowability and marginal improvement in the strength. By increasing the admixture dosage to 4.0%, the flowability and strength are improved. For both admixture dosages, the mixing regimes (D) and (E) show the best flowability improvement and highest compressive strength.

5.3 Effect of curing time

The AAC mixture with CWP to aggregate ratio (1:2.5) and 4% admixture is used to examine the effect of curing time (i.e., 24 and 48 hours) at 60°C. **Figure 23** shows the effect of curing time on the 7 days compressive strength. The compressive strength increases as the curing time increases. A similar trend is reported for metakaolin-based AAC [87]. Although increasing the curing time improves the compressive strength, the application of shorter curing time is considered from the point of reducing the energy consumption.

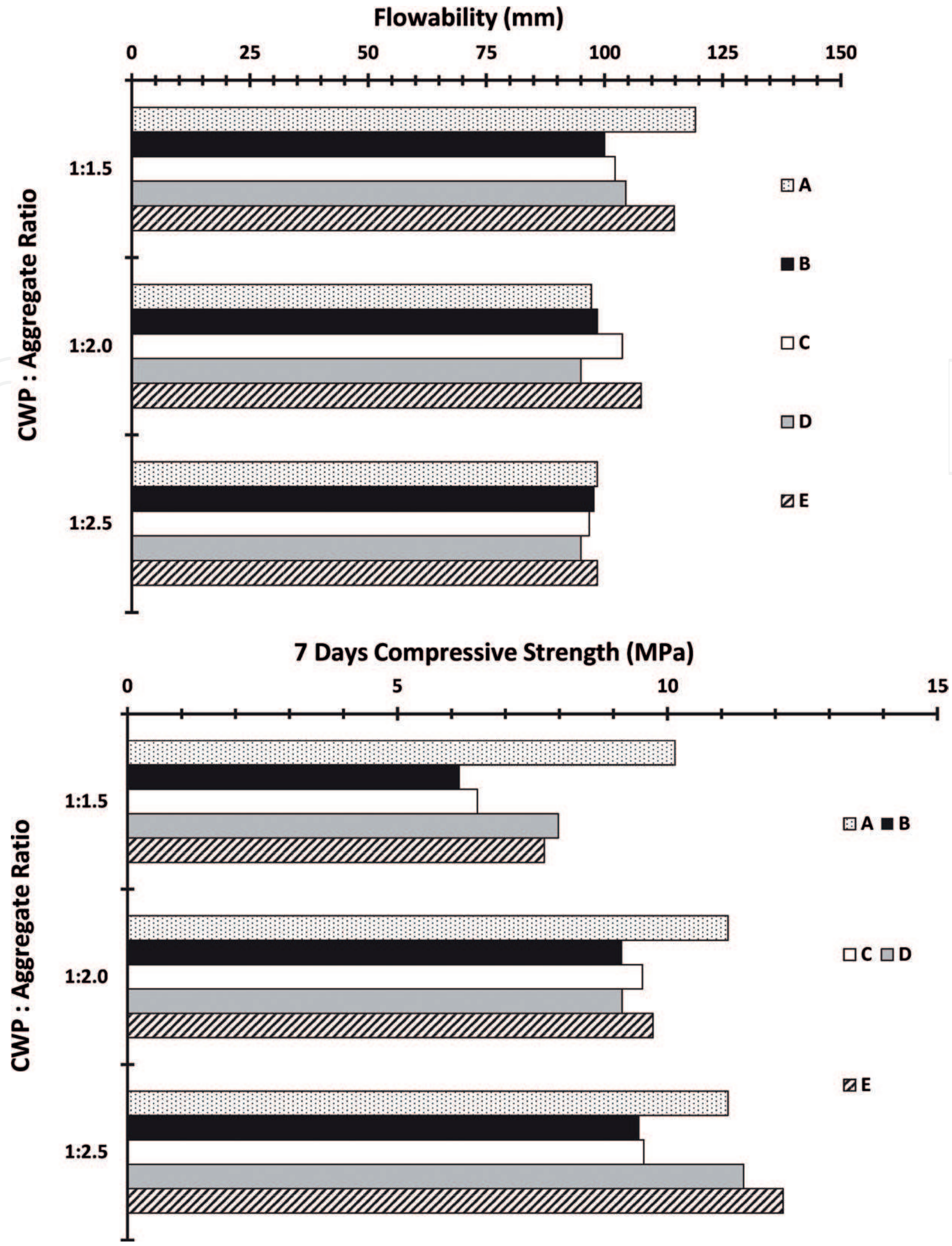

Figure 22.
Flowability and 7 days compressive strength as affected by CWP to aggregate ratio.

Mixing regime	Flowability (mm)		7 Days compressive strength (MPa)	
	1.5%*	4.0%*	1.5%*	4.0%*
A	95	107	12	14
B	95	107	10	12
C	99	110	11	13
D	110	116	13	15
E	112	117	14	16

*Superplasticizer admixture dosage by weight of the CWP.

Table 10.
Effect of admixture on flowability and 7 days compressive strength.

5.4 Effect of slag content and curing regime

Several studies investigated the use of slag in making AAC [88–92]. Slag proved to be a suitable material in making AAC. Slag is characterized by having some

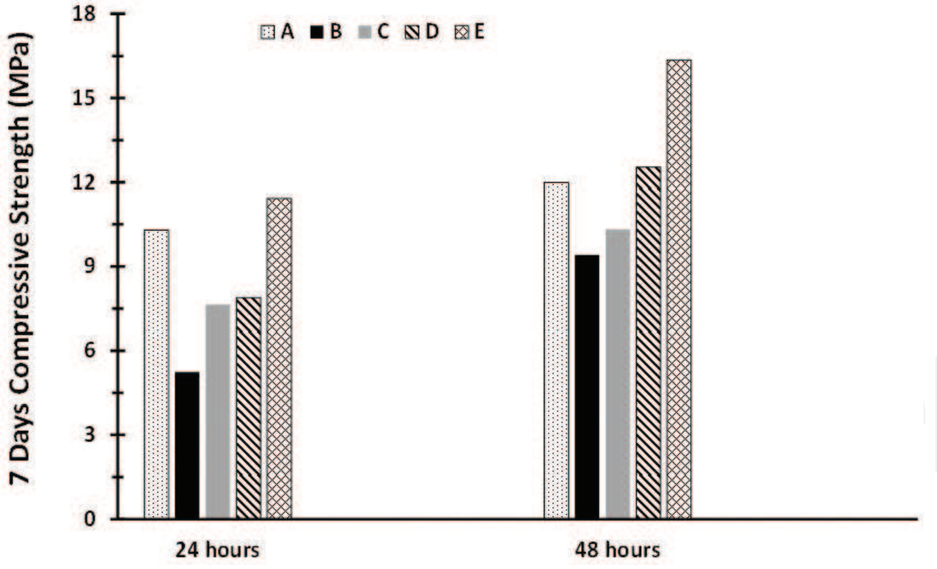

Figure 23.
Seven days compressive strength for the AAC mixture with CWP to aggregate ratio 1:2.5 as affected by curing time at 60°C.

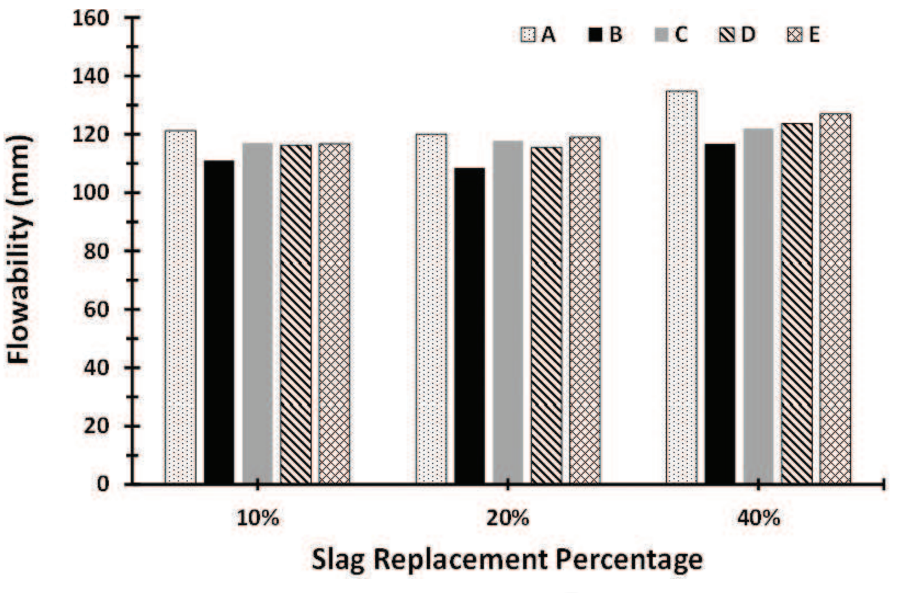

Figure 24.
Flowability of AAC including CWP and slag.

hydraulic reaction due to the existence of calcium oxide (CaO) beside the existence of silica and alumina for the alkali activation. Therefore, slag is used to replace part of the CWP. This will help improve the flowability of the AAC mixture and improve the strength development without the need to increase curing time. The AAC mixture with CWP to aggregate ration 1:2.5 and 4% admixture is used to assess the effect of including slag as a binder material in addition to the CWP. The slag replaced the CWP with 10, 20 and 40% by weight. The AAC mixtures including slag are subjected to three curing regimes; air curing, 24 hours at 60°C followed by air curing, and 24 hours at 60°C followed by water curing for 6 days. **Figure 24** shows the flowability of AAC mixtures including slag and CWP. The inclusion of slag improves the mixtures' flowability. The improvement is proportional to the slag content with the highest improvement at 40% slag.

The effect of including slag with CWP on the 7 days strength is displayed in **Figure 25**. The air cured mixtures showed the lowest strength development. It is observed that the (oven + air) and (oven + water) results are comparable for both the 20 and 40% slag replacements. The strength values are found to increase with the increase in slag % replacing the CWP, with the highest at 40% slag.

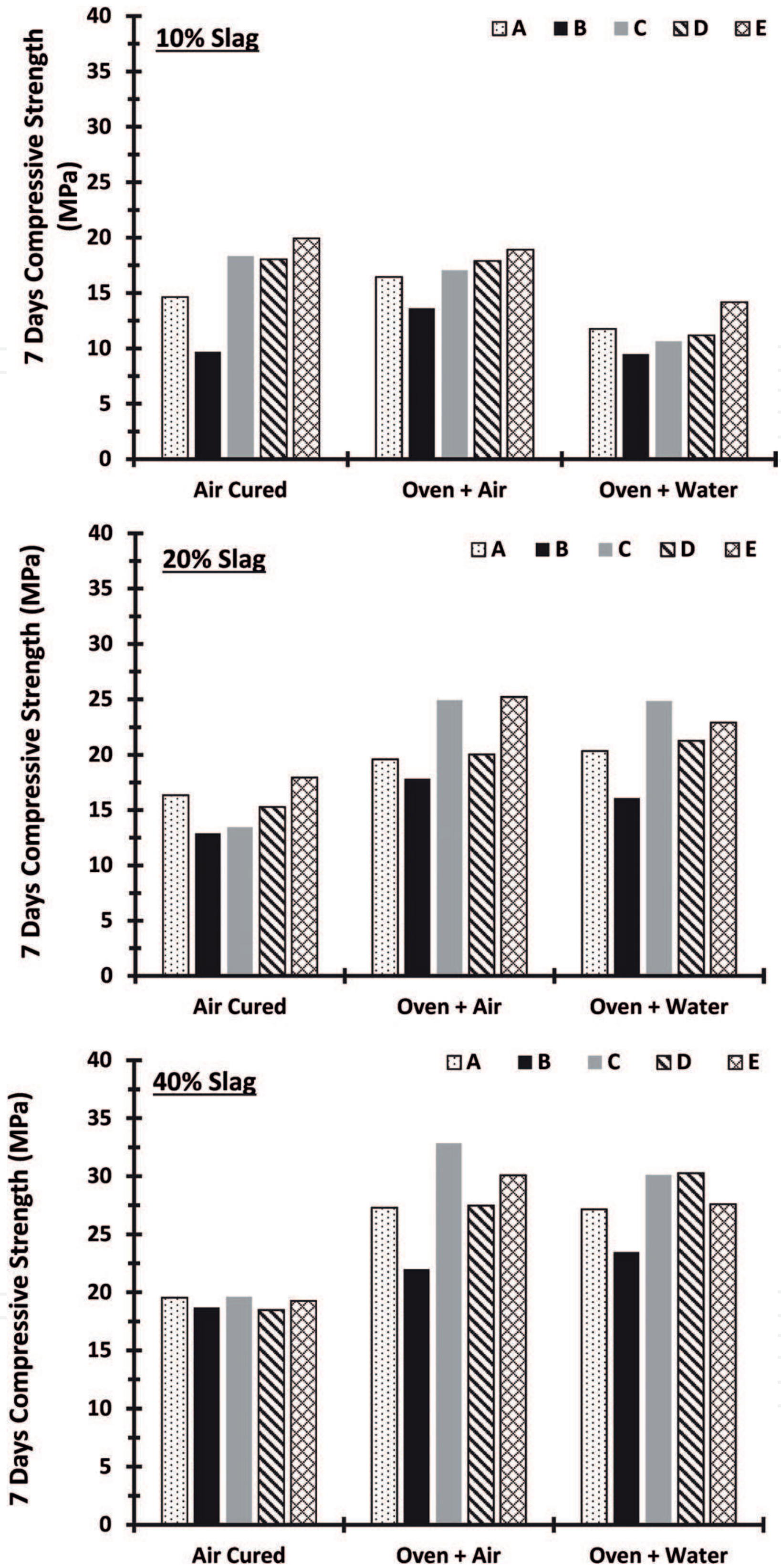

Figure 25.
Seven days compressive strength of AAC including CWP and slag.

The inclusion of slag is beneficial in producing AAC using CWP with a level of replacement of 40%. Based on the flowability and the 7 days compressive strength, the following are the optimum mixture's parameter to make AAC using CWP:

i. the CWP to the aggregate ratio is 2.5,

ii. the alkali solutions mixing regime (D) (i.e., NaOH 60% and KOH 40% mixed) produces suitable flowability and strength;

	Test age (days)	
	7	28
Compressive strength (MPa)	39.3	40.7
Permeable pores %	8.89	8.32
Electrical bulk resistivity (kΩ.cm)	17.9	18.2
Initial rate of absorption (mm/min$^{1/2}$) sorptivity	0.15	0.12

Table 11.
Seven and twenty-eight days results for optimum AAC mixture.

iii. the use of 4% of superplasticizer to improve flowability;

iv. the application of 24 hours at 60°C followed by air curing; and

v. the use of 40% by weight slag to replace CWP.

The performance of an AAC mixture following the above parameters is assessed. **Table 11** summarizes the obtained results. Results show that CWP in combination with 40% slag can produce AAC with strength suitable for different structural applications. The electrical resistivity and initial rate of absorption indicate that the produced AAC is characterized by high durability. The change in the test results values with age indicates that most of the reactions are finished at 7 days of age. Hence there is no need for waiting to evaluate the performance at 28 days of age similar to Portland cement concrete.

6. Conclusions

The CWP contains high silica and alumina content (i.e., >80%). Also, it is characterized by having some amorphous content which shows pozzolanic activity especially at late ages. Therefore, CWP has strong potentials to be used as an ingredient in making eco-friendly concretes.

Using CWP as an ingredient in making CVC is viable. High-performance concrete can be produced by including CWP as partial cement replacement. CWP improves the workability retention of the CVC mixtures. The inclusion of CWP will reduce the early-age strength and slowed the strength development. Significant improvement of CVC durability can be achieved by including high content of CWP. The CVC performance varies according to the CWP content. CWP can be used in the range of 10–20% to improve workability retention and late strength development. A CWP content ranging from 30 to 40% is needed to improve durability. If the performance of mixture requires the combination of workability retention, strength and durability, a CWP content ranging from 20 to 30% can be used to optimize all required characteristics.

CWP can be used as a partial cement replacement to produce SCC that meets international requirements. All fresh concrete properties, except for slump flow, are significantly improved by the incorporation of CWP. The improvement is proportional to the CWP content. Similar to CVC, the inclusion of CWP affected the strength development and enhanced the durability. SCC with improved fresh performance and optimized strength can be produced using 40% CWP as partial cement replacement.

The use of CWP in making AAC showed promising potentials. The production of AAC using CWP should consider the aggregate content of the mixture, the use of superplasticizer admixtures and the use of an alkali solution composed of NaOH and KOH. The combination of slag with CWP improves the workability and strength development without the need for long curing time to conserve energy. The combination of CWP with fly ash can also be an alternative to enhance the performance of the produced AAC.

Finally, CWP has encouraging potentials to be used as an ingredient to make eco-friendly conventional-vibrated concrete (CVC), self-compacting concrete (SCC) and zero-cement alkali-activated concrete (AAC). The concrete industry can and will play a vital role in the sustainable development through the utilization of industrial waste materials.

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