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Utilizing waste latex paint toward improving the performance of concrete

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ABSTRACT

In this paper, incorporating the waste latex paint (WLP) into the conventional concrete as a partial replacement of sand to improve its durability was investigated. The fresh and hardened characterizations, in addition to the durability of concrete, were examined. The slump test was used to evaluate the fresh properties, while the hardened properties were evaluated through the volume of voids and absorption rate, in addition to the compressive, splitting tensile, and flexural strengths tests. The durability performance was evaluated by the surface resistivity, bulk electrical resistivity, as well as freeze and thaw resistance tests. The results showed a reduction in the workability with the addition of WLP, which required high dosages of superplasticizer to maintain the same slump in all the mixtures. Although there was a reduction in the compressive, splitting tensile, and flexural strengths, incorporating the WLP into the OPC concrete improved the durability significantly. Specimens had 5% and 10% of WLP passed the 300 freeze and thaw cycles without deterioration in the relative dynamic modulus of elasticity, compared with the reference mixtures that failed after only 144 cycles. Simultaneously, the surface and bulk electrical resistivity increased by approximately 125% and 138%, respectively, as result of reducing the volume of air voids that was decreased by 9%. The SE images and EDS spectrums showed denser cementitious matrixes with a film of polymeric layer covered the hydration products with adding waste latex paint.

1. Introduction

With rapid population growth, a large amount of waste materials is not properly recycled or disposed of, which affects the environment negatively. According to the EPA [1], the U.S. produced approximately 268 million tons of solid waste during the year 2017, which is 5.7 million tons more than what was generated in 2015. Out of that, less than 40% was recycled. For example, more than 133 million liter of waste latex paint (WLP) are left unwanted each year [2]. WLP represents the largest volume of liquid hazardous wastes produced in the U.S. with 25–30% of all waste materials [3]. WLP could end up either poured down a storm drain or dumped on the ground, which makes the need to find an alternative way crucial as it is a hazardous material that can contaminate soils, the food chain, wildlife, and groundwater As a result, finding a proper disposing of the WLP would help to conserve the natural resources and, in some cases, add advantages to others areas such as enhancing the characterizations of some widely used materials.

The idea of incorporating recycled waste materials partially into concrete has considerably grown recently [4–8]. The recycled waste materials were found to play a role in improving certain key properties of concrete and decreasing its production cost without scarifying its main mechanical characterizations [9,10]. Recycled waste materials such as crumb rubber were used as a partial replacement for the fine and coarse aggregates in concrete and masonry units [5,6]. Other materials, like fly ash and slag, were used as a partial or total replacement of cement in concrete [6,11–14].

WLP is a leftover water-based acrylic material that was produced to be used in painting surfaces. Depending on its base, the WLP could be grouped into two different categories; waste latex paint (water-based) and (oil-based). The WLP typically consists of water, acrylic binder, Titanium Dioxide (TiO_2), extender, and additives. WLP has been successfully integrated into the construction field to produce non-structural concrete elements such as durable sidewalks [3,15,16], highway median barriers [17], previous concrete [18], and concrete blocks [19]. Furthermore, the WLP was used to protect the superstructure of the bridges from chemical attack by overlaying the bridges [2,16,20].

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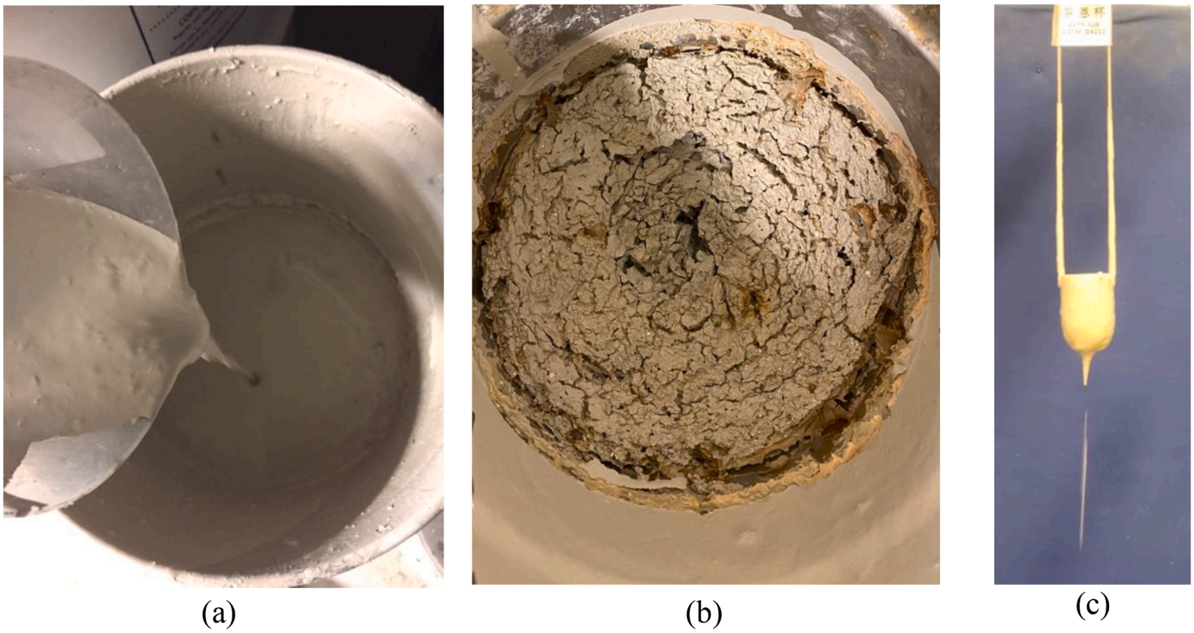

Fig. 1. Waste latex paint, (a) flowable sample, (b) dry sample, and (c) viscosity test.

Previous studies were conducted to investigate the effects of WLP on the fresh, mechanical properties, and durability performance of concrete [2,3,15,19–21]. The workability was investigated when the WLP replaced the mixing water, cement, and water-reducing and air-entraining chemical admixtures. In one of the studies [22], the workability of the cement paste when 4% to 16% replacement of mixing water with assessed WLP contains was studied. An improvement from 175 mm to 200 mm was found up to 4% substitution of the mixing water as a result of a ball-bearing effect associated with higher dispersion of cement particles, and improved matrix dispersion due to the latex polymers that hinder flocculation that increases the flow. However, the workability gradually decreased from 200 mm to 165 mm, due to the increased viscosity of the matrix [22]. In different studies on concrete [3,15,19,20,22], the workability was assessed when 4% to 60% of the mixing water was replaced with the WLP which contains 47% to 59% of water. A positive performance on the workability from 65 mm to 105 mm was realized up to 10% [3], from 58 mm to 160 mm, 180 mm, 180 mm, 120 mm, and 110 mm for 10%, 20%, 30%, 40%, and 60%, respectively [15]. This was due to the dispersing effect of surfactants present in latexes, the effect of ultrafine pigments used as extenders air-entrained increment [15]. In a different approach, where 1% to 10% of the cement weight was replaced with the WLP. The gradual increment of the WLP resulted in a gradual decrease in the workability from 70 mm to 50 mm, 50 mm, 30 mm, 0 mm, and 0 mm for 1%, 2%, 3%, 5%, and 10%, respectively, due to the filling which the solid particles of polymers cause to the concrete voids and make the concrete mix thick [21]. Another study [20], 8 L/m^3 to 16 L/m^3 of the WLP was used to replace the water-reducing and air-entraining, where the workability was improved from 190 mm to 200 mm with 8 L/m^3. However, the 12 L/m^3 and 16 L/m^3 of WLP dosages maintained workability at 190 mm similar to the control mix.

The mechanical properties such as compressive strength, tensile strength, and flexural strength were examined when 5% to 60 % of the WLP substituted the mixing water, cement, and water-reducing and air-entraining chemical admixtures of concrete [3,15,19,21]. In one of the studies [15], where the WLP replaced the mixing water and the W/C ratio ranged from 0.28 to 0.38, the compressive strength followed a dual trend. A gradual decrease was found from 35.8 MPa to 27.6 MPa. 17.0 MPa, and 22.0 MPa, with 10%, 20%, and 30%, however, it increased to 41.1 MPa, and 44.3 MPa, for 40% and 60%, respectively. Similarly, the flexural strength gradually decreased from 5.8 MPa to 5.6 MPa, 5.0 MPa, and 5.3 MPa with 10%, 20%, and 30%, respectively, however, it increased to 6.1 MPa and 6.4 MPa with 40% and 60%, respectively. The reason was attributed to the effect of set retarding, reduction in density, and the gradual increase of the air content. While adding more WLP the mixtures tend to reach or exceed the amount of the air content in high dosages of WLP which results in a decreased compressive strength compared with the control mixture. The same phenomena of the dual trend in the compressive strength was also witnessed when 4% to 12% of the WLP was used with the water-reducing and air-entraining chemical admixtures [19]. The W/C ratio of the WLP mixtures ranged from 0.86 to 0.89. The compressive strength reduced from 21.0 MPa to 15.9 MPa at 4%, however, it increased to 21.6 MPa and 21.3 MPa at 8% and 12%, respectively. That was attributed to the effect of WLP which has either reduced the strength of the cement matrix or retarded the mix by slowing down the speed of the strength to develop. Similarly, the flexural tensile strength was not observably affected. The 12% had the highest flexural tensile strength while 4%, 8%, and 16% were slightly lower compared with the control mixture. In a different study [21], 1% to 10% of the cement weight replaced the WLP was conducted. The compressive strength gradually decreased from 36.0 MPa to 30.0 MPa, 32.0 MPa, 28.0 MPa, 25.0 MPa, and 16.0 MPa for 1%, 2%, 3%, 5%, and 10%, respectively. Similarly, the splitting tensile strength gradually decreased from 2.9 MPa to 2.1 MPa, 2.3 MPa, 2.4 MPa, 2.20 MPa, and 1.8 MPa for 1%, 2%, 3%, 5%, and 10%, respectively.

The durability of the WLP concrete in terms of rapid chloride ion penetration, abrasion, and rapid freeze and thaw cycles was studied when 5% to 60% of the WLP replaced various mix ingredients such as mixing water, chemical admixtures, and cement [15]. The rapid chloride-ion penetration exhibited better performance compared with the conventional concrete with the increment of the WLP up to 25% [3], 60% [15], and 12 dm^3/m^3.[19]. The reason for that improvement is attributed to various reasons such as the pore-blocking effect of the polymers and extender pigments in the WLP [3], the reduction in ion conductivity due to a decreased permeability [3], and the fine pigments in the WLP which increases the resistance of the chloride ions through a mechanism similar to those of silica fume [20]. Furthermore, the lack of polymers in conventional concrete reduces its ability to resist chloride penetration [2]. The resistance of concrete to freezing and thawing cycles when WLP was incorporated was studied [3]. The gradual

Table 1
Chemical compositions of the WLP using X-ray Fluorescence (XRF).

Oxide	TiO_2	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O	P_2O_5	ZnO
Wt. (%)	37.5	22.8	25.5	6.90	2.80	2.00	0.69	0.60	0.40	0.22	0.18

Table 2
Design of the concrete mixtures.

Mix number	CM*	M5	M10	M15	M20
Waste latex paint (%)	0	5	10	15	20
Liquid WLP (kg/m^3)	0	32	65	97	129
Cement content (kg/m^3)	302	302	302	302	302
Coarse aggregate (kg/m^3)	1069	1069	1069	1069	1069
Fine aggregate (kg/m^3)	891	867	842	818	794
Superplasticizer (ml/kg) **	0.8	2.8	4.0	4.8	6.0
Added extra water (kg/m^3)	160	143	126	108	91
W/C	0.5	0.5	0.5	0.5	0.5
Solid latex /Cement (%)	0.0	0.05	0.10	0.15	0.20
Slump (mm)	150	150	165	130	150

The total mixing water equals 160 kg/m^3.
* CM: control mix based on Missouri Department of Transportation mixture.
** Amount of superplasticizer per 1 kg of cement.

increment in the substitution of the mixing water with WLP up to 25% led to an enhancement in the freezing and thawing resistance of concrete up to 300 cycles compared with the control mix. Several reasons were attributed to this improvement [3] such as the formation of the polymeric films in the cementitious matrix, and the reduction in the moisture penetrability when the WLP was incorporated.

The vast majority of the previous studies used the WLP as an admixture or to replace the mixing water with a focus on the fresh properties, mechanical properties, freeze and thaw, and permeability. There are no studies found focused on the durability or either unified the water-to-cement ratio and cement content of the mixtures to give a clear understanding of the WLP behavior itself within the concrete. Therefore, the durability of the WLP concrete is not well understood or discussed in-depth. Moreover, there are not enough studies on the effect of the WLP on the concretes' microstructure using the SEM technique.

This study aimed to evaluate the performance of the concrete, with a specific focus on the durability when different ratios of the WLP replaced the sand. The water-to-cement ratio was fixed to eliminate the impact of the other factors that could blur the effect of the WLP on concrete. Therefore, this study was carried out to give a clear understanding of the effect of WLP itself with focusing on durability performance. This paper investigated the fresh concrete properties (workability), mechanical properties (compressive strength, tensile strength, and modulus of rupture), and durability performance (freeze and thaw resistance, surface resistivity, bulk electrical conductivity, and absorption). In addition, scanning electron microscopy was performed for the paint and WLP mortar samples.

2. Experimental program

2.1. Materials

In this section, the materials used during this study such as waste latex paint, cement, aggregates, and superplasticizer were presented and discussed.

2.1.1. Waste latex paint

This study used WLP sourced from a waste latex paint collector located in Columbia, Missouri, USA. The collected samples displayed different conditions, some were expired, and others were in good condition (Fig. 1). All the water-based WLP samples were mixed together until they became a well-homogenized one sample to reduce the material properties variability since WLP is a non-controlled waste product. Oil-based WLP samples were also collected and investigated in a preliminary study, but due to their inability to harden and homogenize with the concretes' ingredients and therefore it was avoided during this study. The mixed WLP was off-white with 47% solid content, pH of 7.0, and kinematic viscosity of 17.5 mm^2/sec, respectively. The specific gravity of the liquid and solid WLP were 1.29 and 1.62, respectively.

The chemical compositions of the WLP were determined using the X-ray Fluorescence (XRF) analysis (Table 1). Furthermore, the kinematic viscosity was determined using Zahn viscosity cup number 3 (Fig. 1c) with a nominal orifice diameter of 3.8 mm according to ASTM D4212-16 [23]. The cup was submerged in the WLP barrel until filled. Then, the cup was lifted up out of the material vertically and the timer was started as soon as the flow of the WLP begins. Then, the timer stops at the first definite break in the stream at the base of the cup, and the viscosity was measured.

2.1.2. Cement, aggregates, and superplasticizer

Type I OPC was used with a specific gravity of 3.15 conforming to ASTM C150-16 [24]. Dolomite and river sand having specific gravities of 2.76 per ASTM C127-15 [25] and ASTM C128-15 [26] was used as the coarse and fine aggregates, respectively. Sieve analysis was performed for both types of aggregates and it has shown that grading was within the ASTM C33-16 limits [27].

A commercially available high-range-water-reducer (HRWR) polycarboxylate base was used in this study to maintain the workability of the mixtures to be within the aimed range of 125 mm to 165 mm that is recommended by ACI 211.

2.2. Test matrix and specimen preparation

In this section, the mix design, mixing procedures, and casting were presented and discussed.

2.2.1. Mix design

Five mixtures having 5%, 10%, 15%, and 20% of the volume of the sand replaced with WLP (Table 2) were prepared and used during this research program. Preliminary mixtures displayed poor to non-workable concrete when the WLP replacement exceeded 20% and hence this manuscript limited the replacement to 20%. The volume used for the replacement is the volume of the solid content of the WLP. The nomenclatures of the mixtures were started with the letter M standing for mixture followed by the percentage of the incorporated WLP into that mixture.

All mixtures had a water-to-cement ratio (W/C) of 0.5. The calculated water content included both the water in the WLP and the extra added water to each mixture. In trial mixtures that are not reported in this manuscript, adding WLP to concrete mixtures significantly reduced concrete workability. Therefore, superplasticizer was added as needed to each mixture to maintain a slump value within a targeted range of 125 mm to 165 mm (Table 2) without adding extra water. The slump decreased with adding WLP due to the high viscosity of the WLP. Furthermore, the solid particles of the WLP filled the voids in the mixture which increased the friction between the particles resulting in a lower slump value.

2.2.2. Mixing procedures and casting

The mixing procedures followed the ASTM C192-16 [28]. For the mixtures that incorporated WLP, after adding all the ingredients, the WLP was gradually added over one minute and then the mixture was left to continue mixing for another five minutes. It is worth noting that due

Fig. 2. WLP concrete specimens after casting.

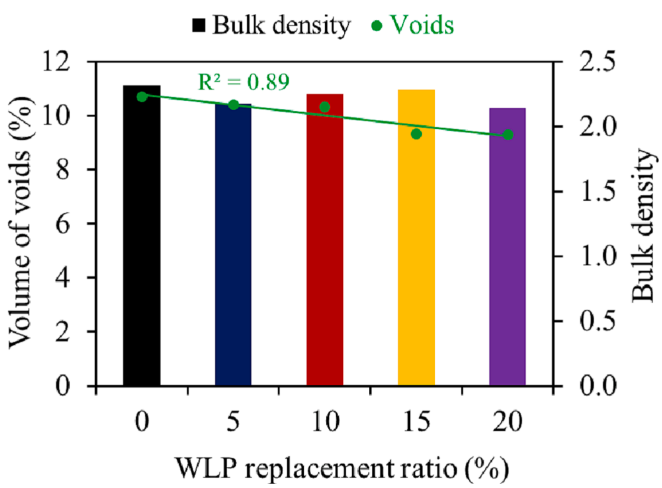

Fig. 3. Volume of voids and bulk density at the age of 28 days for the different mixtures.

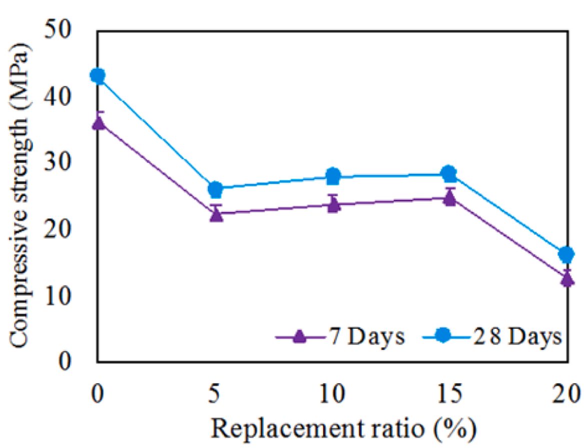

Fig. 4. Compressive strengths of cement mortar with varied WLP ratios at the ages of 7 and 28 days.

to the relatively high viscosity of the WLP, immediately after adding the WLP, the entire mixture tended to display poor workability and the WLP agglomerated the mixture's particles; however, with increasing the mixing time to five minutes, the WLP was dispersed and distributed homogenously in the mixture and subsequently, the workability was improved.

2.3. Specimens testing

2.3.1. Fresh properties

After mixing the concrete, the workability of each concrete mixture was measured using the slump test per ASTM C143-15 [29]. Then, the concrete mixture was placed in 100 × 200 mm cylinders and 75 × 75 × 400 mm prisms for different tests (Fig. 2). All the molds were gently oiled prior to casting and covered for 24 h with a plastic sheet right after casting to prevent moisture loss. After demolding, all the specimens were kept in a moisture curing room at 23 ± 2° C and a relative humidity of 95 ± 5% until the testing age.

2.3.2. Voids and bulk density

The bulk density and volume of permeable voids of the different specimens were determined per ASTM C642-13 [30]. Three 50 mm thick disks were cut from the hardened concrete cylindrical specimens. The disks were dried at 105 ± 5 °C until it reached a constant weight to determine the oven-dried masses (A). Afterward, the disks were left in room temperature to cool down before immersing them in water for 72 hrs followed by boiling the specimens in water for five hrs; then, the specimens were left to cool down gradually to determine their surface-dry masses (C). Finally, the disks were suspended in water, and their apparent masses after immersion and boiling were determined (D). The bulk density and volume of permeable voids were determined per Eqs. (1) and (2), respectively. The average values of the three disks for each mixture were calculated.

$$\textit{Bulk density after immersion and boiling} = C/(C-D) \tag{1}$$

$$\textit{Volume of permeable voids}\,(\%) = (C-A)/(C-D) \times 100 \tag{2}$$

2.3.3. Mechanical properties

Three replicate concrete cylinders were used to determine the compressive and splitting tensile strengths of each mixture at the ages of 7 and 28 days per ASTM C39-17 [31] and ASTM C496-11 [32], respectively. In addition, the flexure strength of each mixture was determined by testing three replicate concrete prisms tested at 7 and 28 days following ASTM C78-16 [33]. The average test results were reported for each test.

2.3.4. Microstructural analysis

To better understand the effects of WLP on concrete properties, five mortar mixtures were prepared using mix designs similar to those of the concrete mixtures investigated in this study but without coarse aggregate. Since the WLP was replaced with the sand, preparing pastes mixtures was not an option to evaluate the matrix of the different mixtures on the microstructural level. Therefore, mortar mixtures were selected instead of concrete mixtures for better visualizations of the matrix under

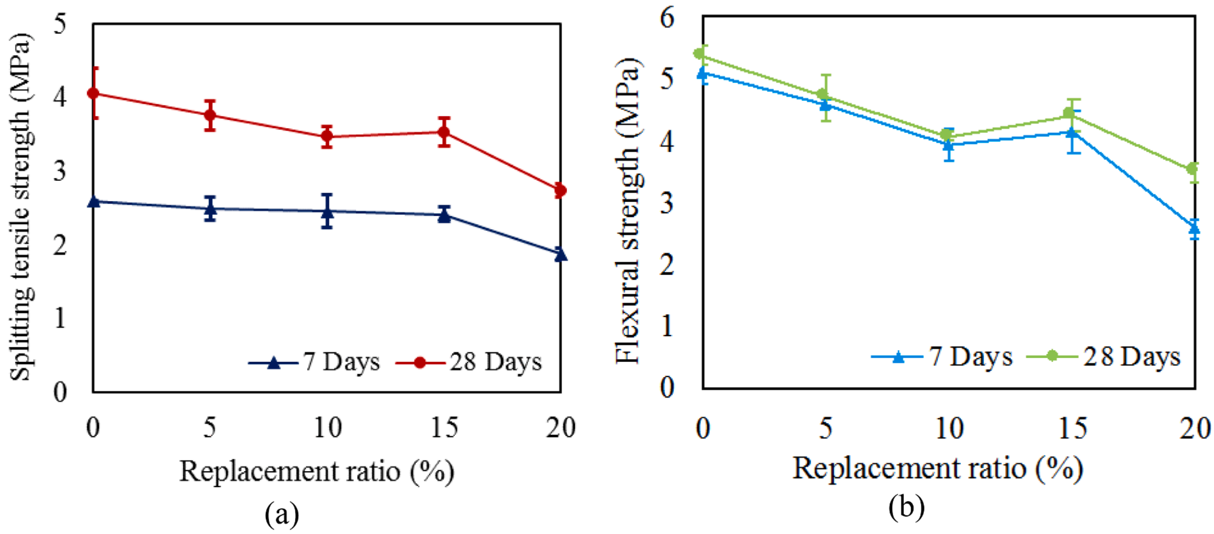

Fig. 5. (a) splitting tensile and (b) flexural strengths of the different mixtures tested at the ages of 7 and 28 days.

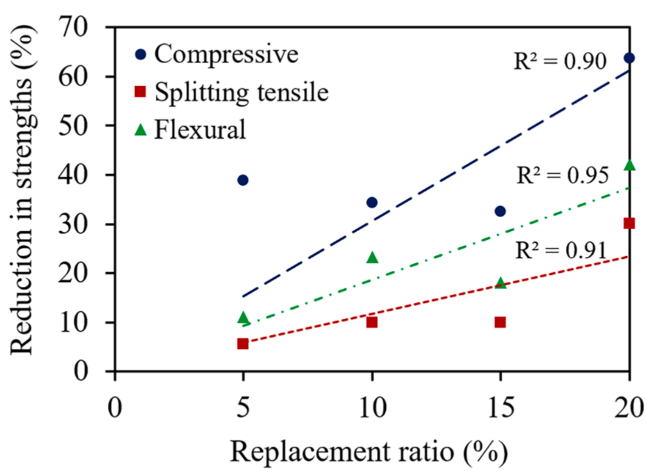

Fig. 6. The average reduction in strengths for different tests.

the microscope. The compactness of the different hardened mortar mixtures was visualized by acquiring secondary electron (SE) images using Scanning Electron Microscopy (SEM). The elemental compositions of the mixtures were determined using energy-dispersive X-Ray spectroscopy (EDS) spectrums.

The mortar mixtures were cast in 50 mm cubic molds and cured as their reference concrete mixtures. The tested samples were taken from the internal body of the mortar cubes to avoid any contamination from the form of oil on the external surfaces of the mortar cubes. Moreover, a sample from the WLP was fully dried in the oven and investigated under the SEM analysis (since the SEM instrument requires dry specimens).

2.3.5. *Selected durability testing*

The surface resistivity of the different concrete mixtures was determined according to AASHTO TP 95 [34]. Four different readings at angles of 0°, 90°, 180°, and 270° around the circumference of each specimen were measured, and their average value was calculated.

The cylinders that were used for the surface resistivity were also used to measure the bulk electrical resistivity per ASTM C1760-12 [35]. The two ends of each specimen were ground to provide flat and smooth surfaces prior to measuring the bulk electrical resistivity. The setup consisted of two steel plates and two pieces of foam in wet condition. The two pieces of foam were placed on the top and bottom of each test cylinder. The steel plates were then placed so that they sandwiched the foam pieces and test cylinders. The average resistivity readings of two replicate specimens per mixture were calculated and reported.

The freeze–thaw of the different concrete mixtures was determined per procedure A of ASTM C666-15 [36]. The standard prisms, 75 × 75 × 400 mm, were fully immersed in water while they were subjected to freezing and thawing cycles. Before subjecting the prisms to the freezing and thawing cycles, the fundamental transverse frequencies of the specimens were measured using ultrasonic pulse velocity test. The specimens were subjected to sets of freezing and thawing cycles where each set consisted of 36 cycles, where the internal temperature of the specimens is lowered from 40 to 0 °F (4 to −18 °C) and back to 40 °F (4 °C) between 2 and 5 h. Testing continued until a test specimen was either subjected to the maximum number of cycles of freeze–thaw, i.e., 300 cycles or the test specimen lost more than 40% of its original relative dynamic modulus of elasticity. The relative dynamic modulus of elasticity (P_c) after c cycles of freezing and thawing and the durability factor (DF) for each specimen was calculated per Eqs. (3) and (4) [36] with c being the number of cycles at which P_c reached the specified minimum value for discontinuing the test or the maximum number of cycles being 300, whichever is less.

$$P_c = \left(n_1^2/n^2\right)x100 \quad (3)$$

$$DF = P_c c/M \quad (4)$$

where n and n_1 are the fundamental transverse frequencies at 0 and c cycles of freezing and thawing, respectively, and M is the specified number of cycles at which the exposure is to be terminated [36].

3. Results and discussion

3.1. *Volume of voids and bulk density*

Adding WLP slightly reduced the density of all mixtures where the density of WLP was lower than the sand, therefore, the density of all mixtures had WLP was lower than that of CM (Fig. 3). Also, it could be seen that although increasing the WLP replacement ratio the volume of the voids decreased gradually, the bulk density of the M10 and M15 was higher than those of M5 (Fig. 3). That phenomena were associated with a lower volume of voids due to higher replacement ratios. However, after increasing the WLP replacement ratio above a certain limit, i.e. M20, a reduction in the bulk density was observed due to the noticeable difference in the densities of sand and WLP.

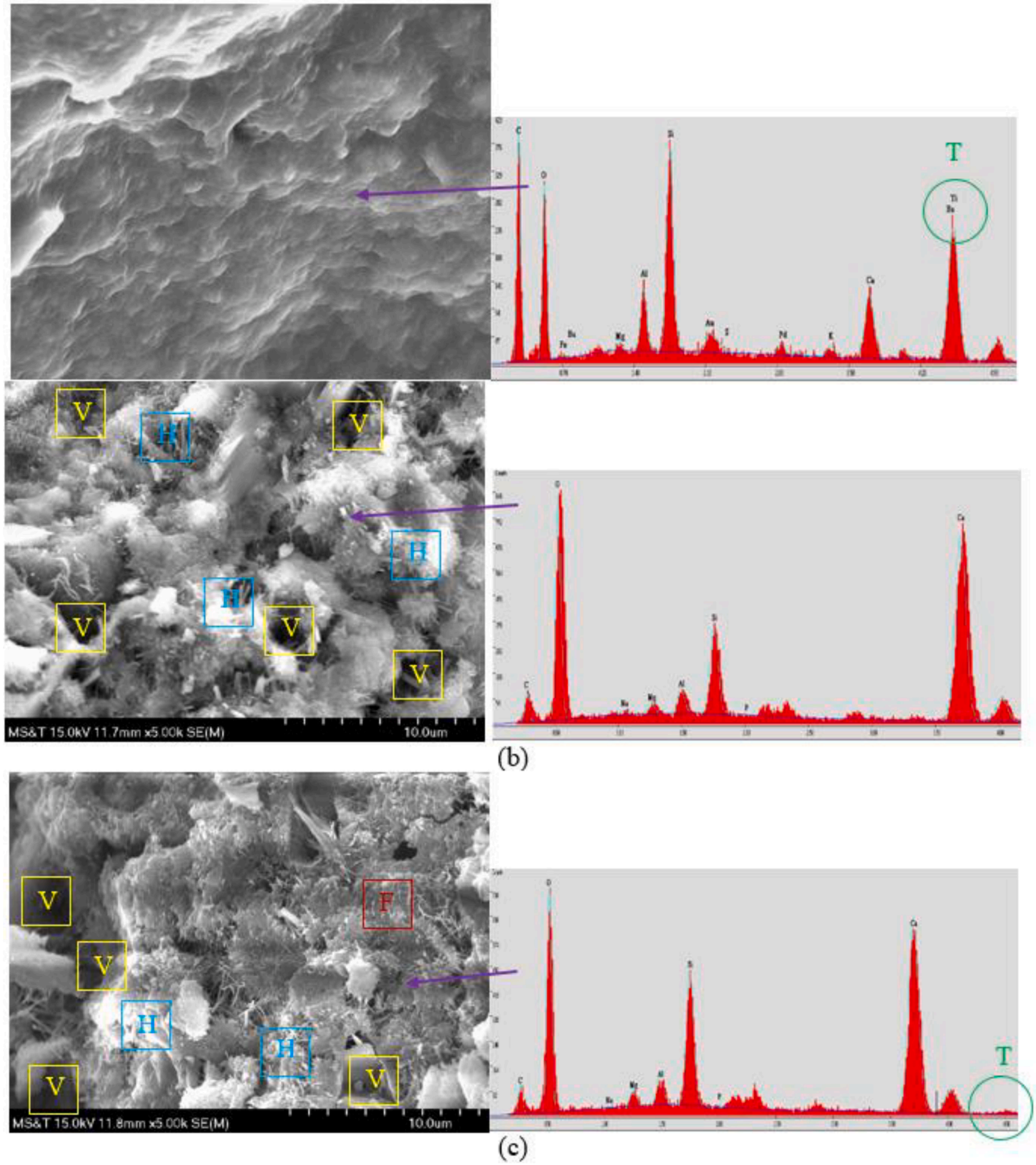

Fig. 7. SE images and EDS spectrums of (a) WLP, (b) CM, (c) M5, (d) M10, (e) M15, and (f) M20.

3.2. Compressive strength

Adding WLP reduced the compressive strength of all mixtures compared to that of the CM with specimens having WLP up to 15% replacement displayed 28-day compressive strengths exceeded 20.7 MPa, i.e., the minimum compressive strength required for structural concrete per ACI 318–08. The stiffness of the WLP is smaller than that of the sand; therefore, with increasing the WLP replacement, a softer mixture was produced resulting in a lower compressive strength. Furthermore, a thin film of WLP enclosed the cement particles' which delayed or inhibited the cement particles dissolution and precipitation; therefore, slowed the hydration reaction and confined the products close to or on the surface of the cement particles which was confirmed using the SEM/EDS analysis presented later in this manuscript [37,38].

The characteristics of the 7-day and 28-day compressive strengths of the test specimens are similar (Fig. 4). The 7-day compressive strength of the CM was 36.0 MPa while those of the mixtures including up to 15% WLP displayed approximately the same compressive strength of 23.6 MPa representing 66% of that of the CM. Increasing the WLP replacement to 20%, significantly decreased the compressive strength reaching 12.6 MPa representing 35% of that of CM. This nonlinear response of the compressive strength function occurred since two contradicting

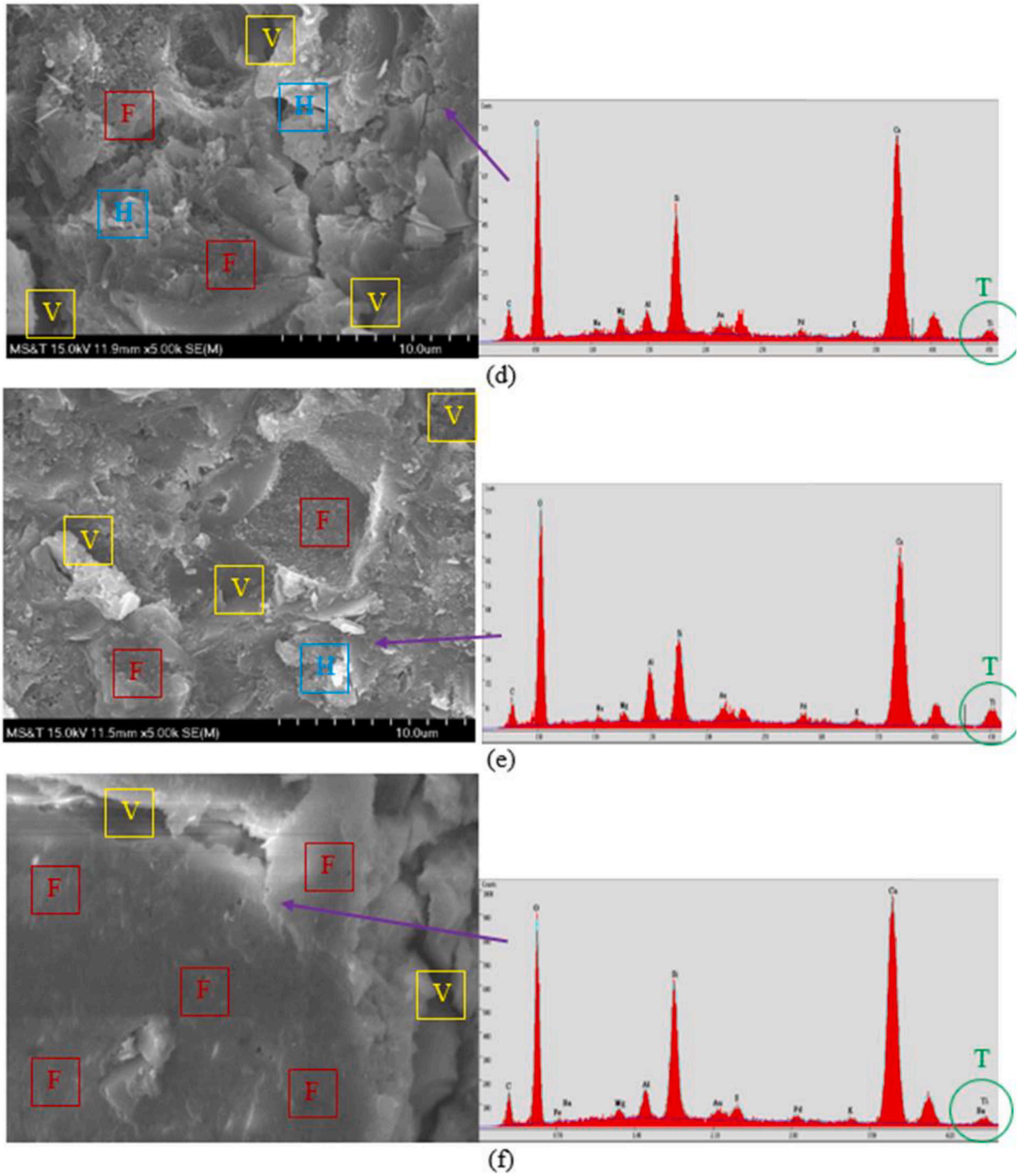

Fig. 7. (*continued*).

parameters affect the strength of concrete incorporating WLP. Increasing the WLP replacement ratio resulted in a reduction in the compressive strength of the mixtures. Increasing the WLP, however, resulted in a reduction in the volume of the permeable voids in the specimens resulting in a more compacted matrix and therefore high compressive strength (Fig. 3). At 20% WLP replacement, the reduction in the compressive strength was more dominant.

At the age of 28 days, the compressive strength of the CM reached 43.0 MPa while those with up to 15% WLP displayed an average of 27.5 MPa representing 64% of that of CM. M20 presented the lowest 28-day compressive strength reaching 16.2 MPa representing 38% of that of the CM. Moreover, except for the M20, the development in the compressive strength for the specimens having WLP was slightly lower than that of CM. The increase in the compressive strength at the age of 28 days compared to those at 7 days for CM was 16% while it was 12% to 15% for M5, M10, and M15. The development in strength reached 22% for M20.

It is worth noting that, the M20 mixture remained unhardened after 24 hrs of casting, and therefore, the demolding process was not possible and delayed for another 24 hrs until the mixture hardened. That observation supported that the WLP resulted in retarding and hindering the hydration reaction and resulted in lower compressive strength. It is

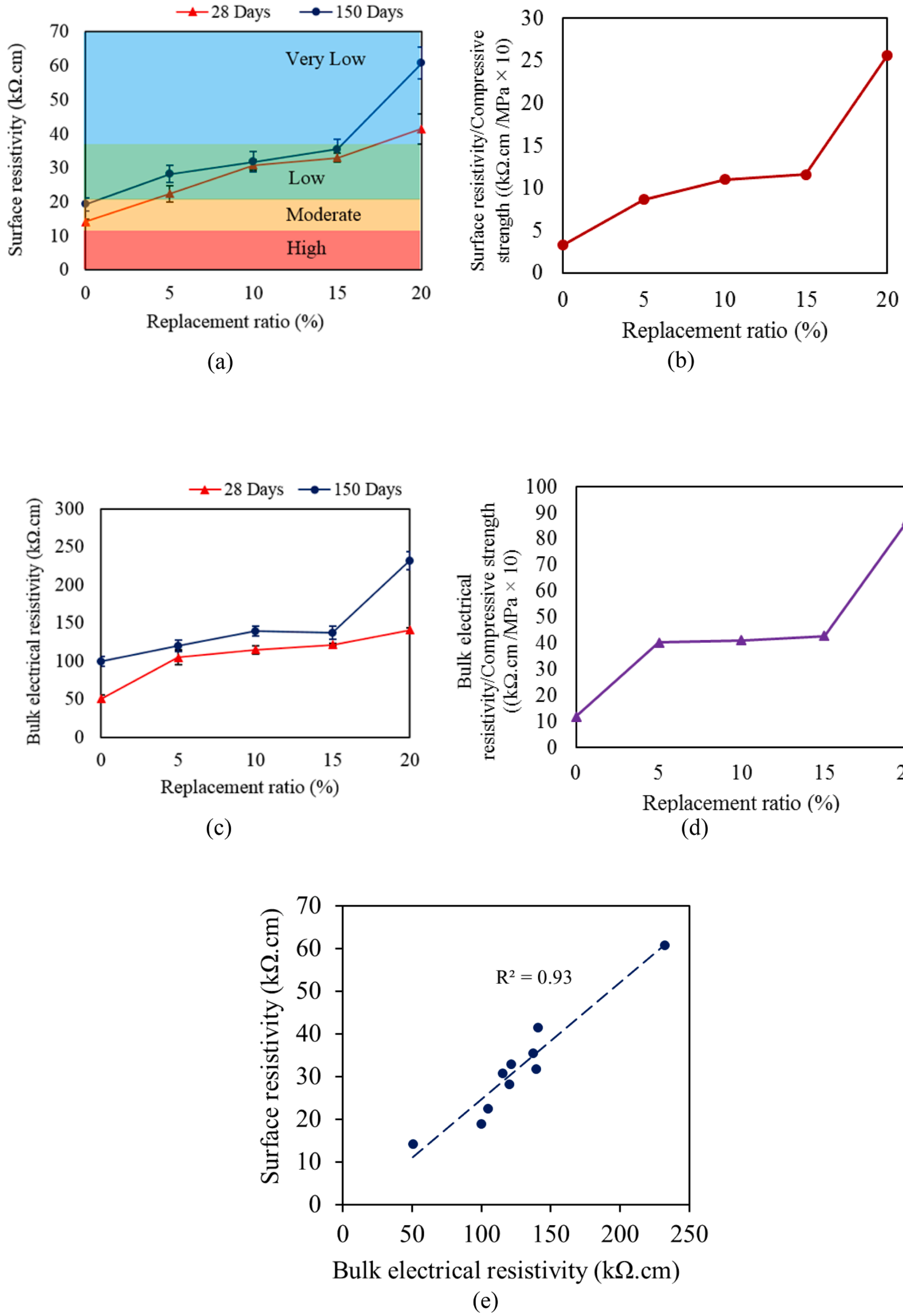

Fig. 8. Surface resistivity and bulk electrical resistivity values of the different mixtures with normalized compressive strength.

worth noting that the effect of the superplasticizer on the delay in setting and hardening of the specimens was assumed to be negligible and was not studied.

3.3. *Splitting tensile and flexural strengths*

Similar to the compressive strength, the splitting tensile and flexural strengths decreased with increasing the WLP replacement ratio in the concrete (Fig. 5). The reductions, however, were at lower rates than those of the compressive strength (Fig. 6). The characteristics of the 7-

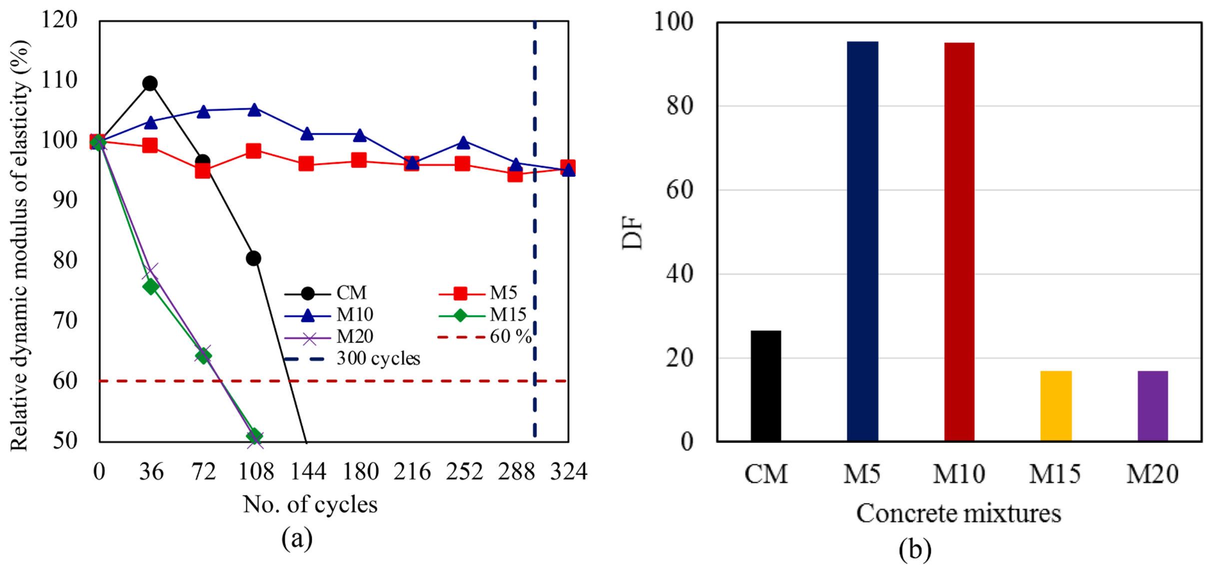

Fig. 9. (a) Dynamic modulus of elasticity, and (b) durability factor of the different mixtures after freeze–thaw cycles.

day and 28-day splitting tensile strengths of the test specimens are similar (Fig. 5). The 7-day splitting tensile strength of the CM was 2.60 MPa while those of the mixtures including up to 15% WLP displayed approximately the same splitting tensile strength of 2.45 MPa representing 94% of that of the CM. Increasing the WLP replacement to 20%, significantly decreased the splitting tensile strength reaching 1.90 MPa representing 73% of that of CM.

At the age of 28 days, the splitting tensile strength of the CM reached 4.05 MPa while those with up to 15% WLP displayed an average of 3.59 MPa representing 89% of that of CM. M20 presented the lowest 28-day splitting tensile strength reaching 2.75 MPa representing 68% of that of the CM. Moreover, the temporal evolution in the splitting tensile strength for the specimens having WLP was slightly lower than that of CM. The increase in the splitting tensile strength at the age of 28 days compared to those at 7 days for CM was 56% while it was 42% to 50% for M5, M10, and M15. The temporal evolution development in the splitting tensile strength reached 45% for M20.

At the age of 7 days, the flexural strength was 5.10, 4.60, 3.95, 4.15, and 2.60 MPa for CM, M5, M10, M15, and M20, respectively. At the age of 28 days, the flexural strength was 5.35, 4.70, 4.10, 4.40, and 3.50 MPa for CM, M5, M10, M15, and M20, respectively.

As it is well known, concrete is a brittle material that is weak under tensile stresses. Incorporating the WLP into the concrete gave flexibility and ductility to it and resulted in a lower rate of reduction compared with those of compressive strength. Moreover, the rate of the reduction in the splitting tensile test was lower than that of the flexural test due to the type of stresses produced from the two tests (Fig. 6). Where the splitting tensile tests produces approximately an equal tensile stress along the entire cross section of the specimen, however, the flexural test produce a triangle of tensile stresses. Therefore, with increasing the tensile stresses on the specimens, the rate of the reduction in the strength was lower with incorporating the WLP and the absolute strength decreased.

3.4. *Microstructural analysis*

The main elements of the WLP were silicon (Si), calcium (Ca), Titanium (Ti), and Aluminum (Al) (Table 1 and Fig. 7a). While calcium, silicon, and aluminum are common elements in the hydration products of OPC and WLP, the Titanium element (noted as "T" in the EDS spectrums) was a unique characteristic element for the WLP in the EDS of the different mixtures. The EDS also indicated the coexistence of the WLP with the hydration products for mixtures where WLP was used.

The compactness of the matrix of the different mixtures increased with increasing the WLP replacement ratio (Fig. 7). That could be noticed as a gradually decreasing number and volume of voids (noted as "V") in the SE images moving from CM to M20. This qualitative observation was also supported by the qualitative measurements of the volume of the voids presented in Fig. 4. Moreover, the WLP formed a thin film (noted as "F" in the SE images) that covered the cement particles and affected the hydration reaction of the different mixtures which could be noticed by the increasing in the flat surfaces and decreasing in the sharp and irregular surfaces of the hydration productions (noted as "H" in the SE images) with increasing the WLP replacement ratio. The CM did not display that flat surfaces and displayed sharp and irregular surfaces. That phenomenon resulted in a lower compressive strength with increasing the WLP replacement ratio.

3.5. *Selected durability evaluations*

3.5.1. *Surface resistivity and bulk electrical resistivity*

Although all the mixtures had the same W/C of 0.50, the CM displayed poor resistivity performance compared to that of WLP mixtures. Electrical current passes through voids in the mixtures; therefore, larger voids content resulted in lower electrical resistivity. Adding the WLP to concrete reduced the volume of voids in the mixtures as well as reduced the pore network connectivity resulting in denser mixtures and higher electrical resistivity.

The surface resistivity value of the CM mixture, at the age of 28 days, was 14.2 kΩ.cm (Fig. 8) indicating that the CM has a moderate risk of corrosion per the classification of AASHTO TP 95 [34]. Replacing the sand with WLP resulted in significant improvement in concrete surface resistivity and corrosion potential. Mixtures M5 through M15 displayed low corrosion potentials with surface resistivity ranging from 22.5 Ω.cm to 33.0 kΩ.cm with the surface resistivity increasing linearly with increasing the WLP content. This represented increases in the surface resistivity values by 58% to 132% compared to that of the CM. Beyond 15% WLP content, i.e., M20 had very low corrosion risk with surface resistivity of 41.5 kΩ.cm representing an increase of 192% in the surface resistivity value compared to that of the CM. The surface resistivity of all specimens except M20 at the age of 150 days increased by 12% compared to those measured at 28 days while the surface resistivity of M20 at 150 days displayed a significant increase of 47% compared to that measured at 28 days.

The bulk electrical resistivity displayed trends similar to those of the surface resistivity with strong linear correlation, with an R^2 value of

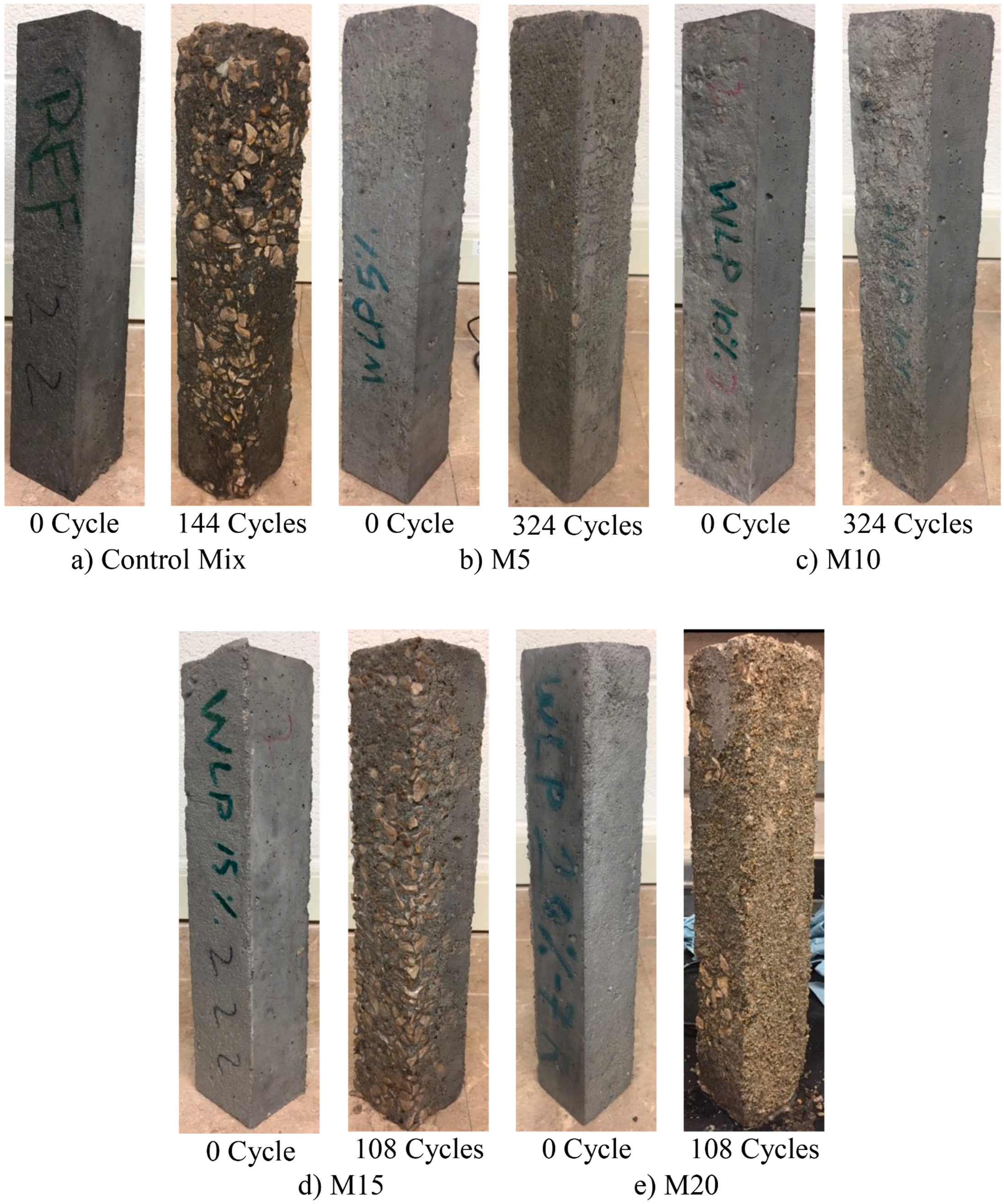

Fig. 10. Test specimens before and after freeze–thaw cycles.

0.93, between both quantities (Fig. 8). The CM displayed a bulk electrical resistivity of 50.6 kΩ.cm while M5 through M15 displayed bulk electrical resistivity values ranging from 104.8 kΩ.cm to 121.4 kΩ.cm. This represented increases in the bulk electrical resistivity values by 107% to 140% compared to that of the CM. M20 displayed slightly higher bulk electrical resistivity of 140.6 kΩ.cm, i.e., the bulk electrical resistivity value increased by 178% compared to that of the CM. The bulk electrical resistivity of all mixtures except M20 at the age of 150 days increased by 16% compared to those measured at 28 days while the bulk electrical resistivity of M20 at 150 days displayed a significant increase of 65% compared to that measured at 28 days.

3.5.2. *Freeze and thaw resistance*

The CM, M15, and M20 mixtures did not pass the freeze–thaw cycle testing per ASTM C666 Procedure A with the mixtures displayed more than 40% reduction in the relative dynamic modulus of elasticity values after only 132, 84, and 84 freeze–thaw cycles, respectively (Figs. 9 and 10). Moreover, the durability factor of CM, M15, and M20 were 26.4, 16.8, and 16.8, respectively. The low freeze and thaw resistance of CM and M20 was attributed to the high volume of the connected voids and the significant low compressive strength, respectively. However, adding the 5% and 10% of WLP improved significantly the freeze and thaw resistance of the mixtures. M5 and M10 displayed 4.5% and 4.8% reduction in the dynamic modulus of elasticity, respectively, after 300 freeze and thaw cycles. Moreover, the durability factor of M5 and M10 were 95.5 and 95.2, respectively. That improvement occurred since adding WLP reduced concrete permeability as confirmed by the measurement of the volume of permeable voids (Fig. 4), surface resistivity and bulk electrical resistivity tests (Fig. 8), and SEM images. Furthermore, WLP is a flexible material that can act as an internal spring in the mixtures that can be compressed during the freezing stage compensating for the increase in the volume of the frozen water; then, the WLP returns to its original size once the water is thawed. Third, the formed polymeric film in the cementitious matrix as shown in the SE images (Fig. 7) can increase its tensile capacity/extensibility [3,37]. Fourth, with increasing the WLP replacement ratio, a shift of the pore size distribution towards a smaller pore size and larger spacing factor was observed which results in a reduction of the moisture penetrability in concrete [3,38].

4. Conclusions

This study investigates the effect of adding the WLP on the workability, mechanical properties, and durability performance of OPC concrete. WLP was sourced from a collector from Columbia, MO, USA, and was in a combination of good and expired conditions. The WLP was added as a partial replacement with the sand with ratios of 5%, 10%, 15%, and 20%. In addition, a reference OPC mixture was prepared for comparison purposes. The compressive, splitting tensile, and flexural strengths were determined as the mechanical properties. The surface resistivity, bulk electrical resistivity, and freeze and thaw resistance were determined as the durability tests. SE images and EDS spectrums were acquired for a clear understanding of the effect of adding WLP. The following conclusion can be drawn from the current investigation:

- The oil-based WLP type was avoided within the course of this study due to its inability to harden and homogenize with the concretes' ingredients.
- The workability of the different mixtures decreased with increasing the WLP replacement ratio due to the high viscosity of the WLP which is equal to 17.5 mm^2/sec. Therefore, higher superplasticizer was added to improve the workability.
- The compressive strength decreased with increasing the WLP replacement ratio due to hindering and slowing the hydration reaction, however, up to 15% WLP replacement, a compressive strength of more than 20.7 MPa was obtained which is enough for the structural applications.
- The splitting tensile and flexural strength decreased with increasing the WLP replacement ratio but at a lower rate compared with that of the compressive strength due to the flexibility and ductility of the WLP that adds to OPC concrete.
- The volume of permeable voids and bulk density decreased with increasing the WLP replacement ratio.
- The SE images showed that a more compacted and denser cementitious matrix was obtained by increasing the WLP replacement ratio. In addition, a film of a polymeric layer covered the hydration products which is supported by the EDS spectrums.
- The surface resistivity and bulk electrical resistivity increased significantly with increasing the WLP replacement ratio which indicated a lower permeable concrete and higher resistance to corrosion.
- The freeze and thaw resistance of the OPC concrete was improved significantly by adding up to 10% of WLP. The specimens had up to 10% WLP passed 324 cycles with a durability factor reaching 95.3.
- Adding the WLP as a partial replacement of sand to the concrete was significantly beneficial for the durability performance in terms of freeze and thaw, surface resistivity, and bulk electrical resistivity.

CRediT authorship contribution statement

Mohamed Leithy: Data curation, Investigation, Writing – original draft. **Eslam Gomaa:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – review & editing. **Ahmed A. Gheni:** Formal analysis, Investigation, Methodology, Project administration, Writing – review & editing, Supervision. **Mohamed A. ElGawady:** Data curation, Investigation, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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