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ORIGINAL ARTICLE

Evaluation of the effect of E-waste on the permeability properties of polymer concrete composites and their behavior in aggressive environments

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Abstract

The rapid increase in the number of electronic products worldwide, in terms of both variety and advanced technology, together with the decrease in costs, has led to the generation of a large amount of electronic waste (e-waste), which has significantly increased environmental pollution. This study was conducted to investigate the hypothesis that the adhesion of polymer binders and plastic origin e-waste will be more effective and stronger, and therefore have a positive effect on the permeability properties of polymer concrete and its behavior against aggressive solutions. For this purpose, quartz aggregates and gravel used as an aggregate in polymer concrete were replaced with 0%, 3%, 6%, 9%, 12% and 15% e-waste. In the study where unsaturated polyester resin was used as a binder, the changes in the permeability properties (capillary water absorption, rapid chloride permeability) of the e-waste polymer concrete and its behavior against aggressive solutions (acid and sulfate attacks) were evaluated after 7, 28 and 90 days. In addition, mechanical experiments were conducted and comparisons were made. After the control concrete, the highest compressive strengths were obtained from the polymer concrete specimens using 3% e-waste, measured as 59.05 MPa, 64.5 MPa and 73.05 MPa after 7, 28 and 90 days, respectively. The research showed that polymer concretes with capillary water absorption coefficient values close to zero after 90 days can be produced with using up to 9% e-waste. The use of e-waste as an aggregate in polymer concrete at 3%, 6% and 9% e-waste, in particular, produced concrete with a high resistance to acid and sulfate attacks. The hypothesis of the study was confirmed after extensive experiments.

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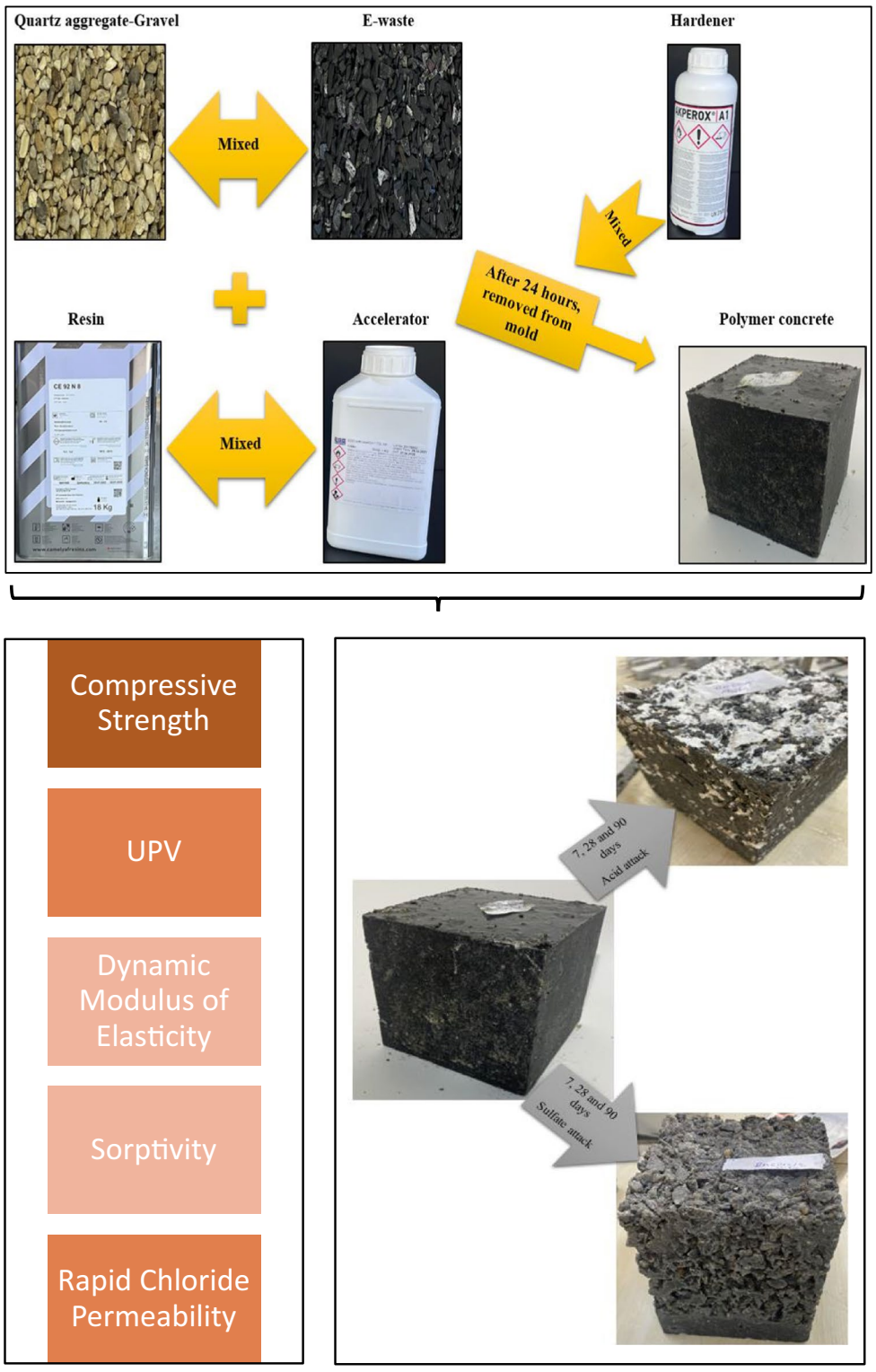
Graphical Abstract



Keywords Polymer concrete · E-waste · Mechanical properties · Sorptivity · Rapid chloride permeability · Aggressive environment

1 Introduction

Polymer concrete, which is produced by combining aggregates and resins, is considered to be a composite material with high performance [1]. Unlike traditional Portland cement concrete [2], polymer concrete is widely used as a special type of concrete [3] due to its high corrosion resistance [4], short curing time [5], superior strength [6] and durability [7], high adhesion [8] and flexural strength [9]. In this way, polymer concretes serve as an ideal material in applications, such as sewer pipes [10], precast elements [11], manholes [12], highways [13], bridges [14], insulation works and manufacturing requiring maintenance and repairs [15]. Instead of cement and aggregates used in traditional concrete, resin as a binder material [16] and a quartz aggregate as a filler material are generally used in polymer concrete production [17]. Resins [18] such as polyester [19], epoxy [20], vinylester [21], acrylic [22] are the most commonly used resin types used in polymer concrete. Epoxy resins are costly [23], while acrylic resins exhibit a variable performance against temperature [22]. Polyester resins have various advantages and are more preferred in practice over other resins due to their superior strength properties [24], low curing time and lower cost [25]. Unsaturated resin is a linear polymer with lipid and unsaturated double bonds [16]. To obtain a denser polyester composition and to improve the performance of polyester resins, hardening and accelerating chemicals are used [26]. In this way, the cross-links of unsaturated polyester composites are improved, which has been found to contribute significantly to the properties of polymer concretes [18].

On the other hand, the rapid increase in the number of electronic products worldwide, in terms of both variety and advanced technology, together with the decrease in costs, has led to the generation of large amounts of electronic waste (e-waste), which has significantly increased environmental pollution [27]. The fastest growing type of solid waste worldwide is e-waste [28]. This type of waste can be collected from telephones, basic household appliances, batteries, computers, health equipment and all kinds of electronic parts [29]. According to the 2020 global e-waste monitoring report [30], approximately 53.6 million metric tons of e-waste was generated, of which 17.4% was recycled and 82.6% was not recycled. The worldwide e-waste estimate for 2030 is 74.7 million metric tons [31]. Containing many harmful elements (e.g., cadmium, arsenic, lead, mercury, nickel, barium and selenium) [32], e-waste is disposed of by unregistered workers, incinerated, discarded as garbage or exported to developing countries [33].

Numerous studies on the performance of polymer concrete have been conducted by various researchers from the past to the present. For example, it was reported that the parameters that affect the mechanical properties of polymer concrete are the type [34] and ratio of resin [35] and the type [36] and ratio of mineral additives [37], nanomaterials [38] and waste [39] that can be included in the production process. Additional studies such as those investigating the fatigue performance [40] and durability [41] of polymer concrete [42] and innovative studies such as those introducing 3D printable polymer concrete [43] and fiber-reinforced polymer concrete [44] have begun to be included in the literature.

Studies using e-waste as an aggregate substitute in construction technology in general and in concrete production in particular are still limited and new. It has been emphasized in various studies that density [45] and compressive [46], flexural [47] and tensile strength [48] decrease as a result of the use of e-waste as an aggregate in concrete [49]. It has been stated that with the use of e-waste in concrete, thermal properties improve [50] and abrasion loss decreases [51]. Recently, studies have been conducted in which e-waste was used together with fibers [52], bacteria [53] and reinforcement applications [54] to improve the performance of the concrete.

The study published by Bulut and Şahin [7] is the only study that could be found in the literature in which e-waste was used as an aggregate and its effect on the mechanical properties of polymer concrete was investigated. This study is based on the hypothesis that "the adherence/adhesion of e-waste of plastic origin with polymer binders will be more effective and stronger, therefore the effect of these wastes on the permeability properties of polymer concretes and their behavior against aggressive solutions will be positive". For this purpose, a quartz aggregate and gravel used as an aggregate in polymer concrete were replaced with 0%, 3%, 6%, 9%, 12% and 15% e-waste. In the study where unsaturated polyester resin was used as a binder, the changes in the permeability properties (capillary water absorption and rapid chloride permeability) and the behavior of the polymer concrete with e-waste aggregates against aggressive solutions (acid attack, sulfate attack) were evaluated after 7, 28 and 90 days. In addition, fresh density, compressive strength, ultrasonic pulse velocity (UPV) and the dynamic modulus of elasticity tests were also performed and comparisons were made.

1.1 Research significance

The study is unique in many respects. For the first time, apart from the mechanical properties of e-waste aggregate polymer concrete, its permeability properties and their behavior against harmful solutions, such as acid and sulfate, will be examined at early, middle and advanced ages. By 2025, the global need for aggregates in the concrete industry is

expected to increase to 59% [55]. As a natural consequence of this increase, aggregate resources are expected to decrease significantly [56]. Considering that we live in the electronic age and e-waste is generated as a result of mass production, it is of great importance to incorporate e-waste into polymer concrete to reduce environmental pollution and to evaluate recycling processes within the scope of the concept of sustainable concrete. Thus, the waste material will be used in the construction industry and a new aggregate alternative will be introduced to the literature. In addition, as a result of the study, it will be revealed which type of resins that form the binding material in polymer concrete will exhibit superior performance with which ratio of e-waste.

Table 1 Technical properties of unsaturated polyester resin

Properties	Concentration (%)
Unsaturated polyester resin (Orthophthalic based)	~ 60
Styrene	~ 40
Physical state	Liquid
Color	Yellowish
Smell	Characteristic styrene odor
Flash point	~ 34 °C
Ignition point (Solvent)	~ 490 °C
Explosion limits (Solvent)	Lower limit is 1.1%; Upper limit 8.0% (volume)
Vapor density	Heavier than air
Water solubility	Insoluble
Specific weight	1.13 gr/cm^3
Viscosity	475 ± 75 cp
Gelling time (25 °C)	4 ± 1 min
Hardness	Minimum 35 Barcol
Flexural strength	Minimum 100 N/mm^2 (MPa)
Tensile strength	Minimum 55 N/mm^2 (MPa)

2 Experimental methodology

2.1 Materials

In this study, unsaturated polyester resin was selected as the binder material, which constitutes the main element in polymer concrete production. Unsaturated polyester resins are used more than other resins due to their superior mechanical properties, low cost and ease of accessibility [57]. Information about this resin is given in Table 1.

The quartz aggregate, gravel and e-waste constituted the filling material of the polymer concrete in this study. To obtain a uniform aggregate size distribution, sieve analysis was performed according to the TS EN 933-1 [58] and TS 802 [59] standards. The maximum aggregate grain size of 16 mm was between the recommended standard curves (A16/B16) shown in Fig. 1. The specific gravity of the quartz aggregate was 2.64 g/cm^3 and the specific gravity of the gravel was 2.625 g/cm^3 and 2.61 g/cm^3, respectively.

Images of quartz aggregate are provided in Fig. 2.

The SEM analysis image showing the internal structure of the quartz aggregate used in the study is given in Fig. 3. From Fig. 3, it can be seen that quartz aggregates, which are widely used in polymer concrete production due to its high compatibility with resin [60], has low porosity and crystalline shapes [61].

Technical specifications of the quartz aggregate obtained from the manufacturer are given in Table 2.

The e-waste used in this study was obtained from the Exitcom Recycling company (Kocaeli/TR) and was shredded

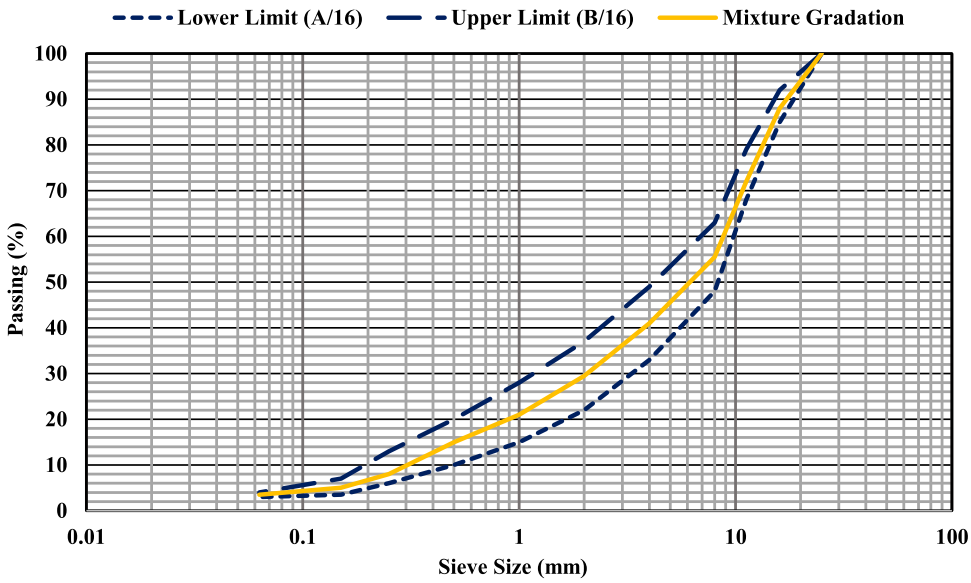


Fig. 1 The grain size curve of mixture

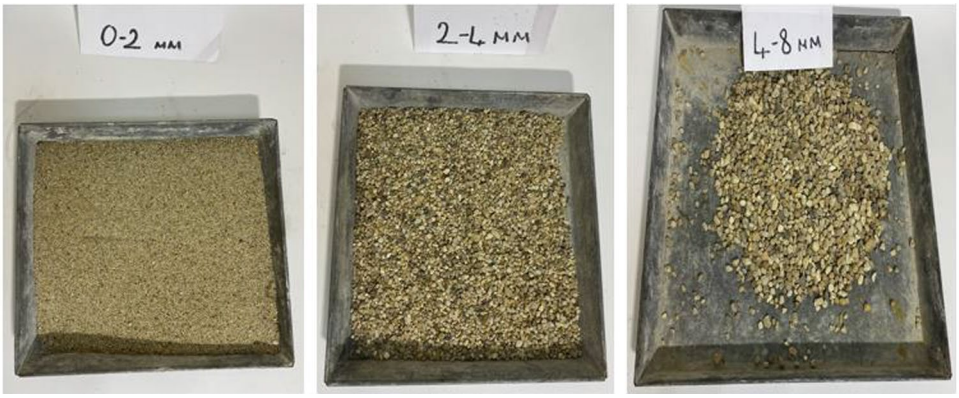


Fig. 2 Images of quartz aggregates after the sieve analysis

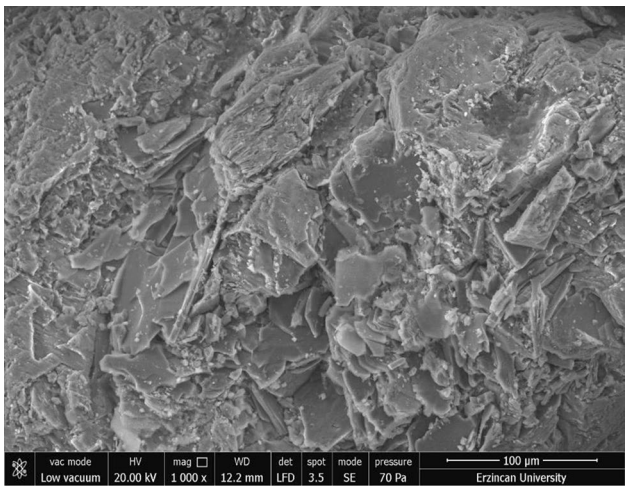


Fig. 3 SEM analysis image of quartz aggregate

Table 2 Technical properties of quartz aggregate

SiO_2	93.28%
Al_2O_3	4.13%
Fe_2O_3	0.070%
MgO	0.05%
CaO	0.04%
Na_2O	0.06%
K_2O	2.07%
Ignition loss	0.30%
Hardness	7
Melting Temperature	1785 °C

to aggregate size to be used in the polymer concrete. Instead of using the quartz aggregate and gravel as filling materials, e-waste was used in different proportions and in three classes (0/2 mm, 2/4 mm and 4/8 mm) with a specific gravity of 1.29 g/cm^3. The visuals of the e-waste after the sieve analysis are given in Fig. 4.

The image of the e-waste production as a result of SEM analysis is given in Fig. 5.

Polyester hardener, which initiates the chemical reaction between the monomer and resin and thus ensures the formation of cross-links, and a polyester accelerator, which acts as an accelerator of the chemical reaction, were used in the production of polymer concretes. Technical information about the hardener and accelerator are given in Table 3.

2.2 Parameters and concrete mix design

The first parameter selected in the study was e-waste, which was used in different proportions as an aggregate instead of the quartz aggregate and gravel. E-waste was chosen instead of the other aggregates, considering that e-waste of plastic origin will adhere better with the plastic-origin resins that form the binding material of polymer concrete. Thus polymer concrete with superior permeability properties and a high resistance to aggressive solutions can be obtained. While e-waste is used as an aggregate in polymer concrete production, its usage ratios have been determined in line with studies found in the literature. Accordingly, when the studies were examined [45], it was found that the optimum e-waste usage ratios varied between 10% and 15% as a result of various experiments [62]. In this study, the e-waste ratios were 0%, 3%, 6%, 9%, 12% and 15%, taking into account the ratios in the literature. In addition, three different day parameters (7, 28 and 90 days) were selected as the second parameter to examine the early, middle and advanced age behavior of the polymer concrete. The polymer concrete produced as control concrete did not contain any e-waste. As a result of intensive preliminary experiments, the proportions of the hardener and accelerator used in the production of the polymer concrete were 1% and 0.1%, respectively, and were kept constant in all mixtures. In addition, the resin/filler ratio was 15–85% in all polymer concrete groups. For each batch, a 150 × 150 mm cube (for compressive strength and acid and sulfate attack tests 6 specimens) and a 100 × 200 mm cylinder (for capillary water absorption and rapid chloride permeability tests 4 specimens) were produced. Considering

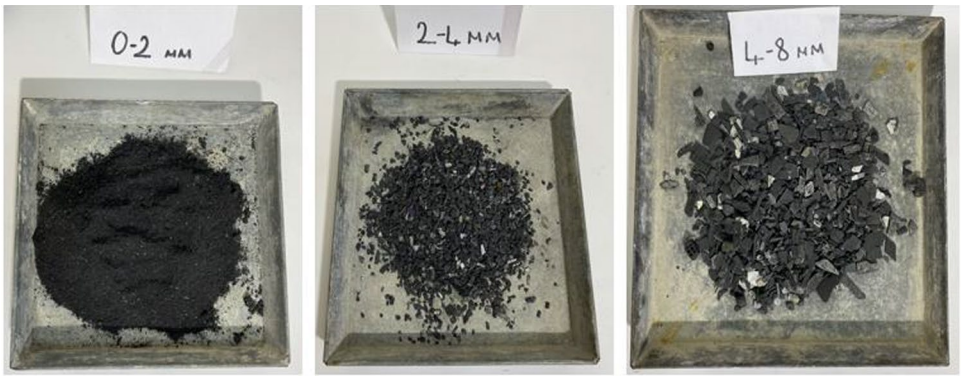


Fig. 4 Images of e-waste after the sieve analysis

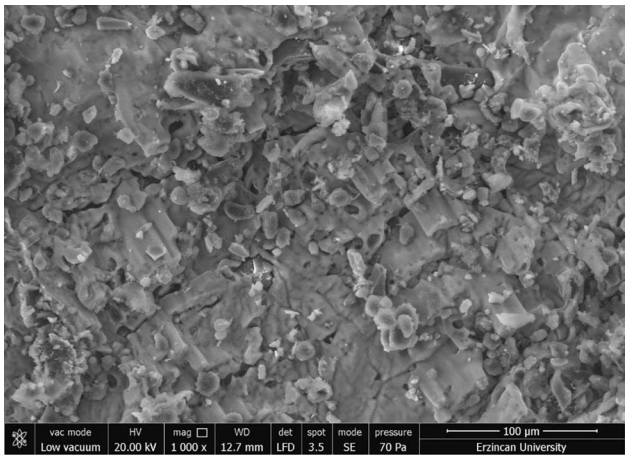


Fig. 5 SEM analysis image of e-waste

Table 3 Technical properties of hardener and accelerator

Hardener	
Product Code	AKPEROX A1
Product Description	Methyl Ethyl Ketone Peroxide mixture
Density	1.16 gr/cm^3
Color	Colorless
Active Oxygen Content	9.4%–9.6%
Peroxide Content	40%
Accelerator	
Product Code	COBALT OCTOATE (EGEDry 12201)
Usage places	As a dryer in oil paints, as a polyester catalyst accelerator, in sticking rubber to metal
Density	0.98 gr/cm^3
View	Clear Fluid
Co metal (%)	10
Total solid (%)	63

the day parameters, a total of 108 cube and 72 cylinder specimens were produced and the results of all the experiments were averaged and calculated.

Table 4 Polymer concrete mix design (kg/m^3)

Code	E-waste	Fine Aggregate (Quartz Agg.)	Coarse Aggregate (Gravel)	Polyester Resin
C		836.41	1203.92	360
EW3	33.92	811.53	1194.87	360
EW6	67.85	786.28	1186.20	360
EW9	101.77	761.03	1177.16	360
EW12	135.70	736.15	1168.11	360
EW15	169.62	710.89	1159.44	360

To interpret the data obtained from the experiments more clearly and easily, coding was used. Accordingly, the e-waste abbreviation was indicated by its first letters, the e-waste ratios were indicated by the numbers after the letters (without using the % sign), and the test days were indicated by the numbers after the '/' sign. For example, the code EW12/90 represented polymer concrete containing 12% e-waste and indicated that this concrete was tested on day 90. The control concrete was denoted by the letter C. The concrete mix design prepared for the production of the polymer concrete is given in Table 4. In Table 4, the numbers representing the day of the experiments are not included.

2.3 Polymer concrete production

In the production process of polymer concrete obtained by combining aggregate and resin materials, polymerization and curing are initiated by adding low dosages of hardener and accelerator materials into the resin. Thereafter, coarse and fine aggregates are added to the liquid mixture and mixed. The material, which completes the hardening process in a short time, consists of a composite structure bonded together with a solid resin binder, which has a uniform aggregate distribution [63].

In the production of polymer concrete, all the filling materials consisting of the quartz aggregate, the gravel and the e-waste were mixed in a concrete mixer for 60 s. Then,

an accelerator was added to the resin and after mixing for another 60 s, it was poured over the filler materials and the whole mixture was mixed in the mixer for 3 min. Finally, a hardener was added to the mixture and the whole mixture was mixed for 2 more minutes. The fresh concrete placed in the molds was subjected to vibration for 2 min with the help of a table type vibrator. After 24 h, the concrete was removed from the molds and cured in air until the test day. The diagram showing the polymer concrete production process is given in Fig. 6.

2.4 Experimental studies

A fresh density test of the polymer concrete was performed according to the TS EN 12350-6 [64] standard. According to the TS EN 12390-3 [65] standard, compressive strength tests of the 150 × 150 mm cube specimens at the end of 7, 28 and 90 days were conducted using a 3000 kN capacity ELE press device with a loading rate of 0.4 MPa/s. UPV tests on the 150 × 150 mm cube specimens were performed after 7, 28 and 90 days. Eq. (1) is used to calculate the velocity of sound in concrete [66].

$$V = L/t \tag{1}$$

In Eq. (1), L represents the distance traveled by the sound between the probes (0.15 m) and t represents the experimental measurement of the sound transmission time in seconds. After obtaining the average velocities of each polymer concrete specimen using UPV measurements, the dynamic modulus of elasticity values were calculated based on ASTM C 597 [67]. Eq. (2) provided by this standard was used in the calculations:

$$E_d = \frac{\rho V^2(1+\mu)(1-2\mu)}{1-\mu} \tag{2}$$

Accordingly, E_d is the dynamic modulus of elasticity of the polymer concrete in MPa and ρ is the density of the concrete (kg/m^3). In addition, the UPV value is represented by V and Poisson's ratio is represented by μ. The ASTM C 1585 [68] standard was used for the capillary water absorption test of the cube specimens of the polymer concrete, which were performed at the end of 7, 28 and 90 days. Rapid chloride ion permeability tests of the polymer concrete specimens were performed according to the ASTM C 1202 [69] and AASHTO T 277 [70] standards. The rapid chloride ion permeability experiment was performed on the 7-, 28- and 90-day-old cube samples. Acid and sulfate attack tests were performed on the cube specimens according to the ASTM C 267 [71] and ASTM C 1012 [72] standards. Two specimens of each polymer concrete were immersed in 5% H_2SO_4 and 5% Na_2SO_4 solutions for 7, 28 and 90 days. After the visual evaluation, the weight and compressive strength losses of the specimens (based on the weights and compressive strengths before and after exposure) were calculated (in percentages). The visualization of this experiment is given in Fig. 7.

3 Results and discussion

3.1 Fresh density

Fresh density values of the polymer concrete specimens are given in Fig. 8. Accordingly, when e-waste was added to the mixtures, the fresh density results decreased compared to the control concrete. The highest fresh density value was obtained in control concrete (C) with 2240 kg/m^3 and the lowest fresh density value was obtained

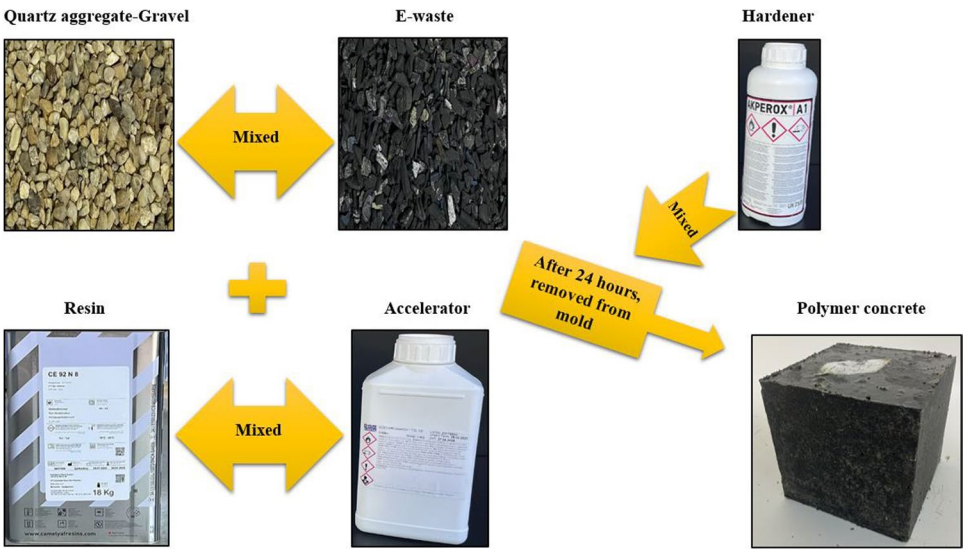


Fig. 6 Diagram showing the polymer concrete production process



Fig. 7 Implementation visualization of the acid and sulfate attack test

in sample EW15 with 1920 kg/m^3. The increase in the e-waste ratio decreased the fresh density values of the polymer concrete. When this ratio increased from 3% to 15%, a fresh density loss of 13.74% occurred. The fact that the specific gravity of e-waste (1.29 g/cm^3) is much lower than that of the quartz aggregate (2.64 g/cm^3) and gravel (2.625 g/cm^3 and 2.61 g/cm^3) is considered to be the main reason for the decrease in the fresh density of the polymer concrete. Similar observations were reported in studies [73] where e-waste was used as a substitute for a natural aggregate in concrete [74].

Not only do fresh density values play a determining role on the fresh and hardened properties of concrete, but they also enable the concrete to be evaluated within the classification of lightweight, normal and heavyweight concrete. The densities of polymer concrete are approximately 2100 kg/m^3 in the literature. Depending on the resin type and ratio [75], it has been brought to the literature for the first time

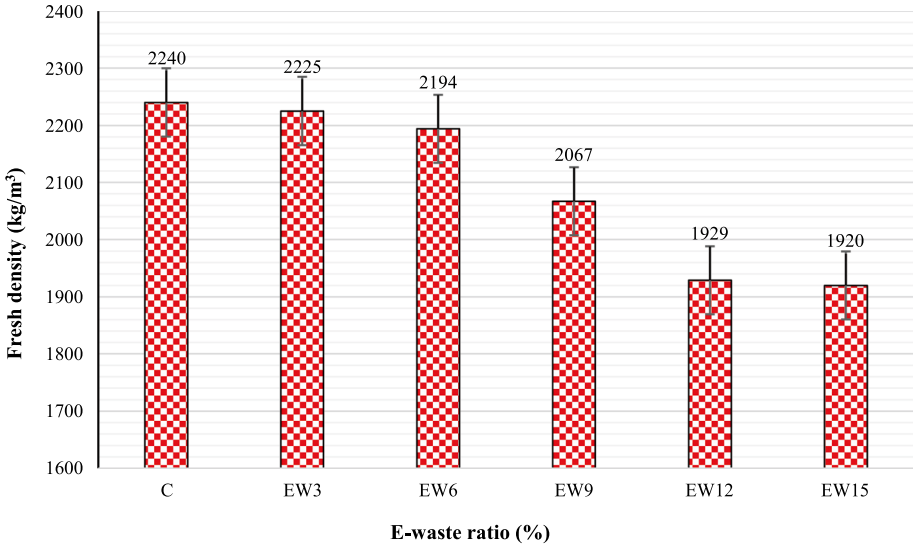


Fig. 8 Relationship between fresh densities and the replacement rate of E-waste

in this study that lightweight polymer concretes can be produced by using e-waste in polymer concrete (for example, the fresh density of 15% e-waste polymer concrete (EW15) is 1920 kg/m^3). In this way, it is thought that both the damages that the structures will be exposed to under earthquake loads can be reduced and a more advantageous production can be made in terms of cost.

3.2 Compressive strength

Figure 9 shows the compressive strength results of the polymer concrete with different e-waste ratios at 7, 28 and 90 days.

It is seen from Fig. 9 that the highest compressive strength was obtained from the control concrete (C/90) at the end of 90 days with 75.75 MPa and the lowest compressive strength was obtained from the concrete coded EW15/7 at the end of 7 days with 33.4 MPa. The compressive strengths decreased with the use of e-waste in the mixtures. Similar findings were obtained in other studies [47] where e-waste was included in different concrete types [76]. It is thought that the hydrophobic structure of e-waste [77] and its relatively weak bond with resin [78] are effective on the decreases in the compressive strength values [79]. It is also thought that the losses in compressive strength may be due to the fact that the e-waste-resin interface transition zone may become weaker with the use of e-waste at increasing ratios [80].

Among the e-waste admixed polymer concrete, the highest compressive strengths were observed in the concrete with 3% e-waste (EW3), which were 59.05 MPa, 64.5 MPa and

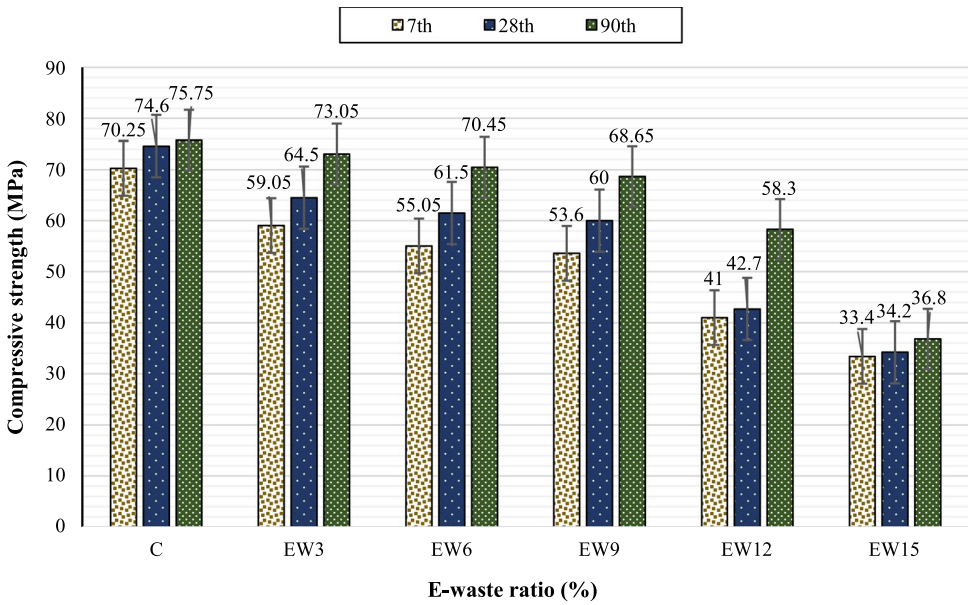


Fig. 9 Relationship between the compressive strength—E-waste ratio according to the number of days

73.05 MPa for 7, 28 and 90 days, respectively. The compressive strengths of the polymer concrete (EW15) with the highest proportion of e-waste (15%) lost between 51.42% and 54.16% from the control concrete depending on the day. In all the polymer concrete specimens, the compressive strengths increased as the curing period increased from 7 to 90 days. For example, this increase was 24% and 28% at the end of 90 days compared to 7 days in the polymer concrete specimens containing 3% and 6% e-waste, respectively. It is thought that the optimum ratio, shape characteristics and particle size of the e-waste used together with the curing time are the determinants of this increase [81]. In this study, the highest compressive strength was achieved in the polymer concrete specimen with 3% e-waste except for the control concrete.

In addition, it was revealed for the first time in this study that polymer concrete with 3%, 6% and 9% e-waste can produce polymer concrete with high strength by reaching 50 MPa and above on all days together with the control concrete. The meaning of these results is considered to be invaluable, considering that high-strength concrete allows for the reduction of cross-sectional areas of structural elements, resulting in concretes with superior mechanical and durability properties (for example, they are widely used in columns, shear walls, foundations and high-rise buildings). Finally, as observed during the experiment, the use of e-waste as an aggregate in polymer concrete reduced the weight of the concrete and improved pre-fracture deformations by exhibiting a ductile behavior [82].

3.3 Ultrasonic pulse velocity

Ultrasonic pulse velocity (UPV), one of the non-destructive testing methods, is widely used to evaluate the quality of concrete. With this method, it is possible to detect cracks, voids and other defects, if any, in the concrete. Therefore, the UPV method was used to measure the quality of the polymer concrete specimens. Figure 10 shows the UPV test results of the polymer concrete specimens depending on the day parameter (7, 28 and 90 days) and the e-waste ratio. As the e-waste ratio increased, the UPV values of the polymer concrete specimens decreased slightly for all days. In another study where e-waste was used in concrete at ratios of 10%, 20% and 30%, it was reported that the UPV results decreased [83]. In the study conducted by Akın and Polat, it was determined that the UPV values of the polymer concrete with waste tires of different sizes were negatively affected as the waste tire ratio increased [39]. Similar behavior was observed in another study where plastic waste was used in normal concrete [75]. It is considered that the high air void content in the polymer concrete, especially in polymer concrete with a high e-waste ratio, and the minimization of ultrasonic sound propagation due to acoustic impedance may have reduced the UPV values [84].

It is also thought that polymer concrete containing more than one component of e-waste with different volumetric concentrations may have negatively affected the UPV values [84]. Finally, it can be said that the use of e-waste in polymer concrete at increasing ratios instead of a quartz aggregate may have increased the porosity of the e-waste mixtures compared to the control concrete and decreased the UPV values, based on a study in which recycled materials were used in unsaturated polyester mortars instead of quartz sand [15].

When the UPV results were evaluated in general, no dramatic or sharp decreases were observed as a result of the use of e-waste at different ratios in the polymer concrete specimens compared to the control concrete. For example,

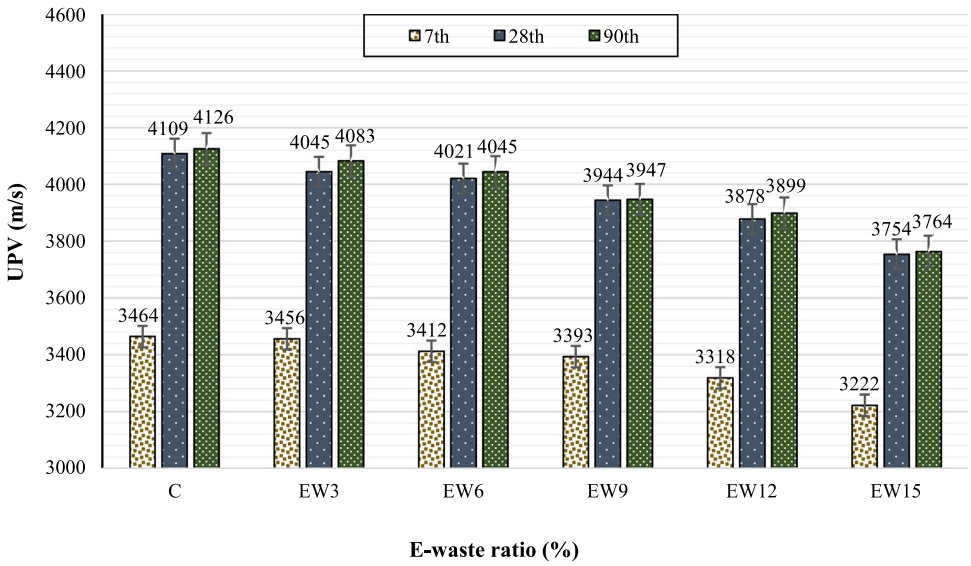


Fig. 10 Change of UPV values according to the E-waste ratio and the number of days

when the 7 day results were evaluated, the UPV of the polymer concrete (EW15/7) with the highest ratio of 15% e-waste (3222 m/s) decreased by 7% compared to the control concrete (C/7) (3464 m/s). At the end of 90 days, the UPV difference between these two concrete specimens increased only slightly to 8.77%. The increase in curing time from 7 to 90 days (from early age to advanced age) brought on an increase in UPV values. For example, while the 7 day UPV result of 6% e-waste polymer concrete (EW6/7) was 3412 m/s, this value increased by 19% to 4045 m/s at advanced age (EW6/90).

As can be clearly seen in Fig. 10, the increase in UPV values of the e-waste admixed polymer concrete from 7 to 28 days was sharp, but this was realized with little differences from 28 to 90 days. Although 28 days as a curing parameter showed a dramatic effect on the UPV results of the e-waste polymer concrete specimens with different ratios, no significant UPV increase could be obtained at advanced ages such as at 90 days. These data have been brought to the literature for the first time in this study as a distinctive result. Among the polymer concrete groups with the e-waste additives, the highest UPV values for all days were obtained from the polymer concrete group with 3% e-waste.

The IS 13311 [85] standard has made a classification according to the UPV results of concrete. Accordingly, concrete with UPV values of 3000–3500 m/s are classified as medium quality, concrete with UPV values of 3500–4500 m/s are classified as good quality and concrete with UPV values greater than 4500 m/s are classified as excellent quality. As a result of this study, both the control and polymer concrete with different e-waste ratios were classified as medium quality for 7 days and as good quality for 28 and 90 days. In addition, this study concluded that even at the maximum e-waste ratio of 15% in the polymer concrete specimens, the concrete quality in terms of UPV will not be significantly affected and will be of good quality at medium and advanced ages.

3.4 Dynamic modulus of elasticity

The elastic modulus, which plays a key role in the analysis and design of structures, is an important parameter for concrete. The dynamic modulus of elasticity, which is a remarkable indicator of the durability of concrete, reflects the compactness of the internal structure of concrete. The dynamic modulus of elasticity test results were calculated with Eq. (2) by assuming the density, UPV values and Poisson's ratio of 0.2 [86] for the polymer concrete specimens [87] and are shown in Fig. 11. Accordingly, in parallel with the UPV test results, the dynamic modulus of the elasticity values of polymer concrete specimens decreased for all days as the e-waste ratio increased. For example, when the 28-day results were evaluated, the dynamic modulus of elasticity (22.04 GPa) of 12% e-waste added polymer concrete (EW12/28) decreased by 23% compared to the control concrete (C/28) (28.73 GPa). At the end of 90 days, the difference between the dynamic modulus of elasticity values of the control concrete and polymer concrete with 3% e-waste (EW3) was 2.7%, while the difference in the dynamic modulus of elasticity increased by about 10 times to 29% when the e-waste ratio peaked at 15%. In another study where e-waste was used as an aggregate in mortars [88], it was reported that the modulus of elasticity values decreased as the e-waste ratio increased.

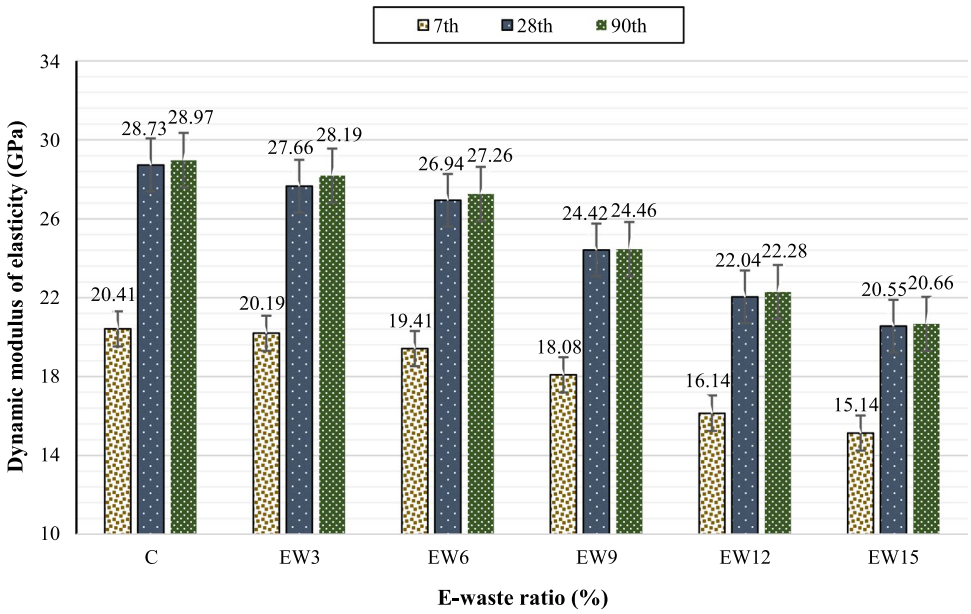


Fig. 11 Dynamic modulus of elasticity versus the E-waste ratio and the number of days

It is thought that the low density of e-waste compared to natural aggregates [89], the weak bond between the filler material and the matrix [90], and the particle size of the wastes involved in e-waste production are effective on the decrease in the dynamic modulus of elasticity results with the use of e-waste at increasing ratios in polymer concrete [91]. It was also stated that the resin type and the amount of resin-filler material [92] will be an important parameter for the modulus of elasticity values of polymer concrete [93].

Just like the UPV results, curing time had a positive effect on the dynamic modulus of elasticity values of the polymer concrete specimens with different e-waste additives. For example, while the 7 day dynamic modulus of elasticity of the polymer concrete with 9% e-waste (EW9/7) was 18.08 GPa, this value increased by 35% to 24.46 GPa at advanced age (EW9/90). Similar observations were made when the e-waste was used in self-compacting concrete [94]. When all the polymer concrete specimens with e-waste were evaluated considering early (7 days), middle (28 days) and advanced ages (90 days), the highest (close to the control concrete) dynamic modulus of elasticity results were observed in the polymer concrete with the 3% e-waste admixture.

3.5 Sorptivity

Figure 12 shows the capillary water absorption test results of the polymer concrete specimens over time (from 7 to 90 days) depending on the e-waste ratio.

As can be seen from Fig. 12, the capillary water absorption coefficients of the polymer concrete specimens increased with the use of e-waste. Although the increase in the results was significant at the early age (7 days) measurement, this situation was experienced with small differences at the middle (28 days) and advanced ages (90 days). In general, the highest capillary water absorption coefficient was obtained in the polymer concrete with the 15% e-waste admixture (EW15/7) with 12.79 and the lowest capillary water absorption coefficient was obtained in the control concrete (C/7) with 0.16. From 7 days to 28 and 90 days, the capillary water absorption coefficients of the polymer concrete specimens with different ratios decreased by 5 to 9 times. It is thought that the low water absorption capacity of e-waste is the determinant of the low capillary water permeability values brought about by the use of e-waste in the polymer concrete [95]. In addition, due to the high adherence of unsaturated polyester resin and e-waste at advanced ages, a dense matrix may be obtained by forming impermeable barriers against water ingress in polymer concrete [96].

Sorptivity, which is a key test that provides information about the durability performance of concrete, is represented by the movement rate of water under the capillarity in the internal structure of concrete. The use of e-waste, especially up to 9%, showed that polymer concrete with capillary water absorption coefficient values close to the control concrete at the end of 90 days (these values are 0.16, 0.25, 0.41 and 0.9, respectively). At the same time, the fact that these values were obtained close to 0 revealed for the first time in this study that polymer concrete containing e-waste can produce almost impermeable concrete in terms of capillary water absorption by exhibiting superior performance.

3.6 Rapid chloride permeability

It is considered that the void systems existing in the internal structure of concrete are an important parameter of rapid chloride ion permeability values. Concretes with low

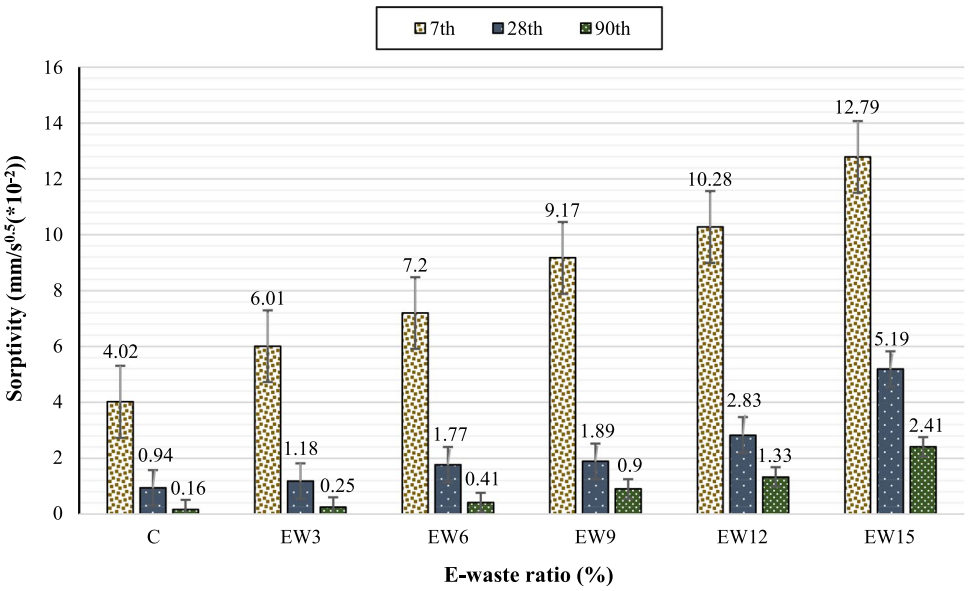


Fig. 12 Relationship between the sorptivities of the mixes and the E-waste ratios

chloride ion permeability are evidence of having fewer voids, a denser microstructure, and a discontinuous pore structure. The values obtained from the rapid chloride permeability experiment of the polymer concrete specimens with different e-waste ratios depending on the measurement day parameter are given in Fig. 13.

According to the results of the experiment, the increase in the e-waste ratio increased the rapid chloride permeability values of the polymer concrete specimens. When the 7 day results were analyzed, for example, it was found that the polymer concrete (EW15/7) with a 15% e-waste ratio reached approximately 6 times higher rapid chloride permeability than the control concrete (C/7) (these values were 527 and 79 Coulomb, respectively). However, just like the capillary water absorption test results, as the age and curing time of the e-waste polymer concrete specimens increased, especially at advanced ages (90 days), the increase in the e-waste ratio had little effect on the rapid chloride permeability values and all the values were negligibly low. For instance, at the end of the 90 days, the rapid chloride permeability values of the control concrete (C/90) and polymer concrete specimens with e-waste ratios between 3 and 9% (EW3/90, EW6/90, EW9/90) were close to each other with 26, 37, 50 and 78 Coulomb, respectively. The fact that these values were close to 0 is proof that an impermeable concrete can be obtained with polymer concrete containing e-waste and is considered to be a scientifically exciting result.

In the literature [97], it was reported that polymers, which are mostly used as coating materials on normal concrete or as modifiers for cementitious mortars, reduce chloride permeability [98]. In addition, it has been reported that [99] polymers have positive effects on the chloride ion permeability of the samples prepared by impregnating concrete [100]. The results of chloride permeability in the polymer concrete specimens produced directly as concrete, which is the distinctive and unique aspect of this study, were promising. It was revealed for the first time in the literature that the use of e-waste from 3 to 15%, especially after 28 and 90 days, showed a strong performance at negligible levels in terms of rapid chloride permeability of polymer concrete.

Finally, according to the ASTM C 1202 [69] the concrete specimens were classified according to the results of the rapid chloride ion permeability tests. Table 5 shows the classification of the polymer concrete specimens produced in this study.

As can be clearly seen in Table 5, the rapid chloride ion permeability test results of the polymer concrete specimens with e-waste are classified as low or negligible. Thus, it has been proven for the first time that e-waste can be used as an aggregate in polymer concrete to produce concrete with a superior performance against chloride permeability, which is an important durability problem.

3.7 Acid attack

Weight losses, compressive strength losses and visual evaluations of the polymer concrete specimens with different e-waste ratios exposed to acid attack for 7, 28 and 90 days were analyzed in detail.

3.7.1 Weight loss of acid attacked polymer concretes

Figure 14 shows the weight losses of the polymer concrete specimens under acid attack on different days (in percentages).

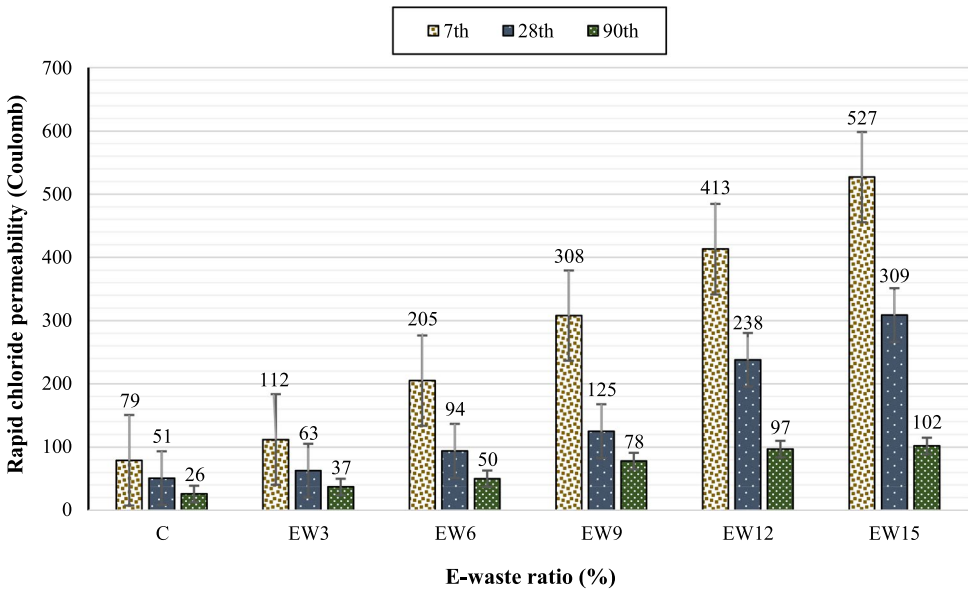


Fig. 13 Rapid chloride permeability results of the mixes

Table 5 Rapid chloride ion permeability classes and concrete groups [69]

Amount of electrical charge passing through concrete (Coulomb)	Evaluation of concretes in terms of chloride ion permeability	Mix code
>4000	High	-
2000–4000	Medium	-
1000–2000	Low	-
100–1000	Very low	EW3/7, EW6/7, EW9/7, EW9/28, EW12/7, EW12/28, EW15/7, EW15/28, EW15/90
< 100	Negligible	C/7, C/28, C/90, EW3/28, EW3/90, EW6/28, EW6/90, EW9/90, EW12/90

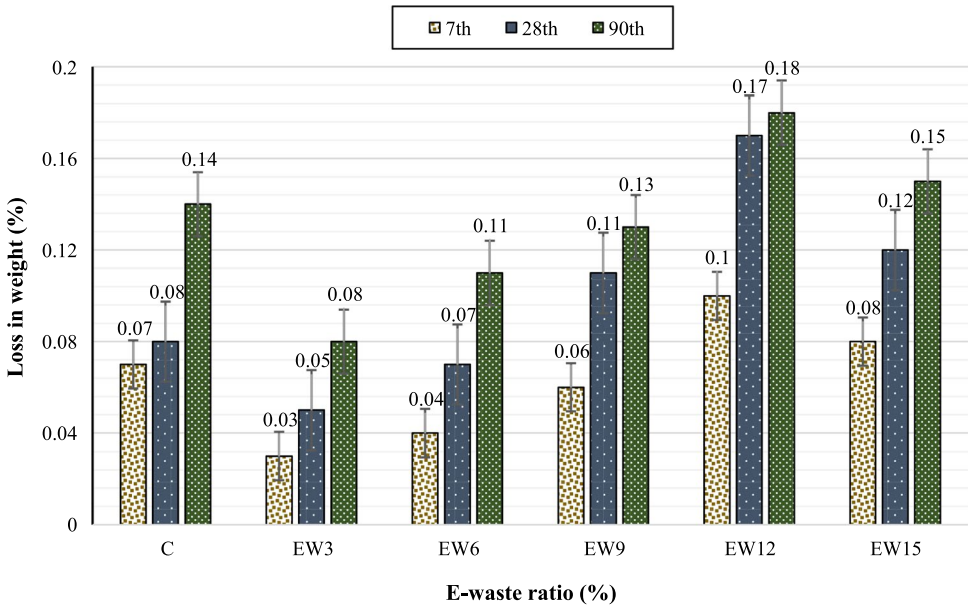


Fig. 14 Loss in weight of the acid attacked polymer concretes

Accordingly, when the e-waste ratio of 3% was included in the production of the polymer concrete specimens, the lowest weight losses were experienced after the acid attack for all days, including the control concrete. For example, when the percentage weight losses of the polymer concrete specimens exposed to acid for 28 days were analyzed, while the control concrete (C/28) experienced a 0.08% weight loss, this loss decreased by 37.5% to 0.05% in the 3% e-waste polymer concrete (EW3/28). This result is thought to be due to the fact that the compatibility of the polyester resin and hardener and accelerator materials in polymer concrete production with a 3% e-waste ratio exhibits an optimum adherence and polymer concrete with high performance, especially workability, as observed during the experiment. As the proportion of e-waste increased, the weight loss also increased, peaking at 0.17% in the 12% e-waste polymer concrete (EW12/28). A similar situation was observed in the 7 day and 90 day results. From early age (7 days) to advanced age (90 days), the acid attack increased the weight loss of the polymer concrete specimens. In general, the weight losses of both the control and polymer concrete specimens with different e-waste ratios after the acid attack were found to be at low percentage levels. In one of the rare studies in the literature, it was reported that the changes in the weight losses of resin concrete exposed to an acidic environment over time were obtained with small differences [101]. With this study, it can be easily stated that highly acid-resistant concrete can be produced when e-waste is used as an aggregate in polymer concrete at 6% and 9% (compared to the control concrete), especially at 3%.

3.7.2 Compressive strength loss of acid attacked polymer concretes

Compressive strength losses of the polymer concrete specimens exposed to an acid attack for 7, 28 and 90 days are given in Fig. 15.

Just like the weight losses, the use of 3% e-waste in polymer concrete production resulted in the lowest compressive strength loss among all the groups. For example, when the 90 day results were evaluated, while the compressive strength loss of the control concrete (C/90) was 6.4%, this loss decreased by 50% to 3.23% in the polymer concrete with 3% e-waste (EW3/90). As the e-waste ratio increased, the compressive strength losses were 21.78% and 17.66% for EW12/90 and EW15/90, respectively. The 7 and 28 day results showed a similar trend. As with the weight losses, the compressive strength losses increased when the exposure time of the polymer concrete specimens to the acid increased from 7 to 90 days. Another study by Jamshidi et al. [102], which is very few in the literature, also reported that the compressive strength losses of polyester resin concrete were high after 90 days of exposure to an acid solution. The reasons for this result could be that the acid exposed for a long time negatively affects the resin and degrades the polymer concrete (aggregate-polymer matrix interface) with high e-waste ratio, causing microcracks and decreasing its strength [103]. It is also thought that there may be a correlation between the number of pores in polymer concrete compositions and strength reduction levels [21].

On the weight and compressive strength losses experienced by the e-waste polymer concrete specimens after the acid attack:

- Sulfuric acid, which combines acid and sulfate, is damaging to polymer concrete.
- Acid ions damage the polymer chains and deteriorate the polyester resin.
- Disintegration and softening of the aggregates are a result of a possible chemical reaction with the acid solution.
- It is considered that the increase in the e-waste ratio is effective in disrupting the aggregate-polymer matrix interface and in creating a porous internal structure.

Finally, this study revealed that e-waste polymer concrete, especially at 3% and 6%, exhibited superior performance against acid attacks.

3.7.3 Visual evaluation results of acid attacked polymer concretes

Visuals of the polymer concrete specimens exposed to 90 days of an acid attack are given in Fig. 16. Accordingly, the visual damage of the polymer concrete after the acid attack was obtained in parallel with the weight and compressive strength losses. It can be clearly seen in Fig. 16 b that the 3% e-waste polymer concrete (EW3/90), which had the lowest results in weight and compressive strength losses, visually showed a higher resistance to the acid. Even the surface deterioration of the 3% e-waste polymer concrete was limited, and the resin acted as a shield, preventing the acid from reaching the polymer concrete [3]. It was also clearly seen in Fig. 16c and d that the polymer concrete specimens with 12% and 15% e-waste (EW12/90 and EW15/90), where the highest results were obtained in weight and compressive strength losses, suffered the most severe visual damages (exfoliation, capping, abrasion, chipping, crumbling an white staining). Thus, as a result of this study, the weight and compressive strength losses of the polymer concrete specimens after the acid attack and the visual evaluation coincided with each other.

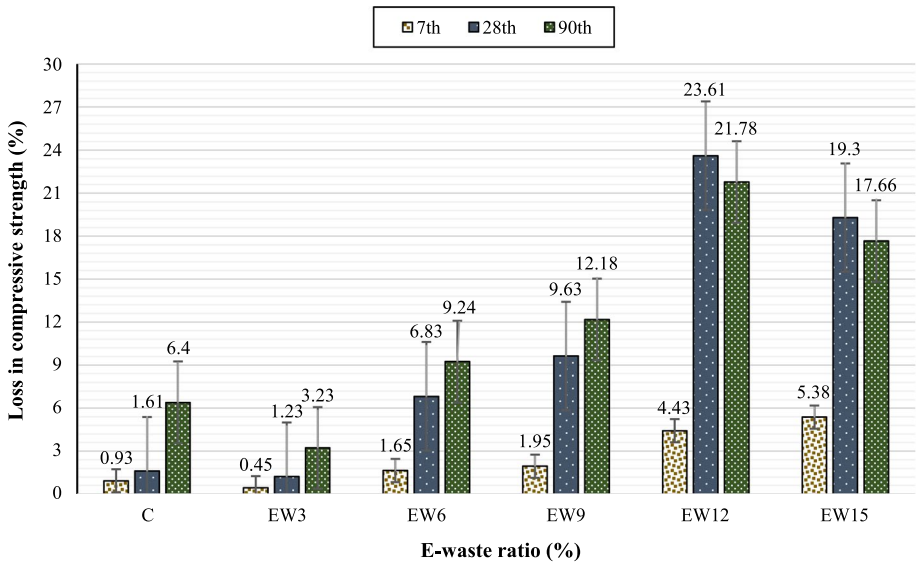


Fig. 15 Loss in compressive strength of the acid attacked polymer concretes

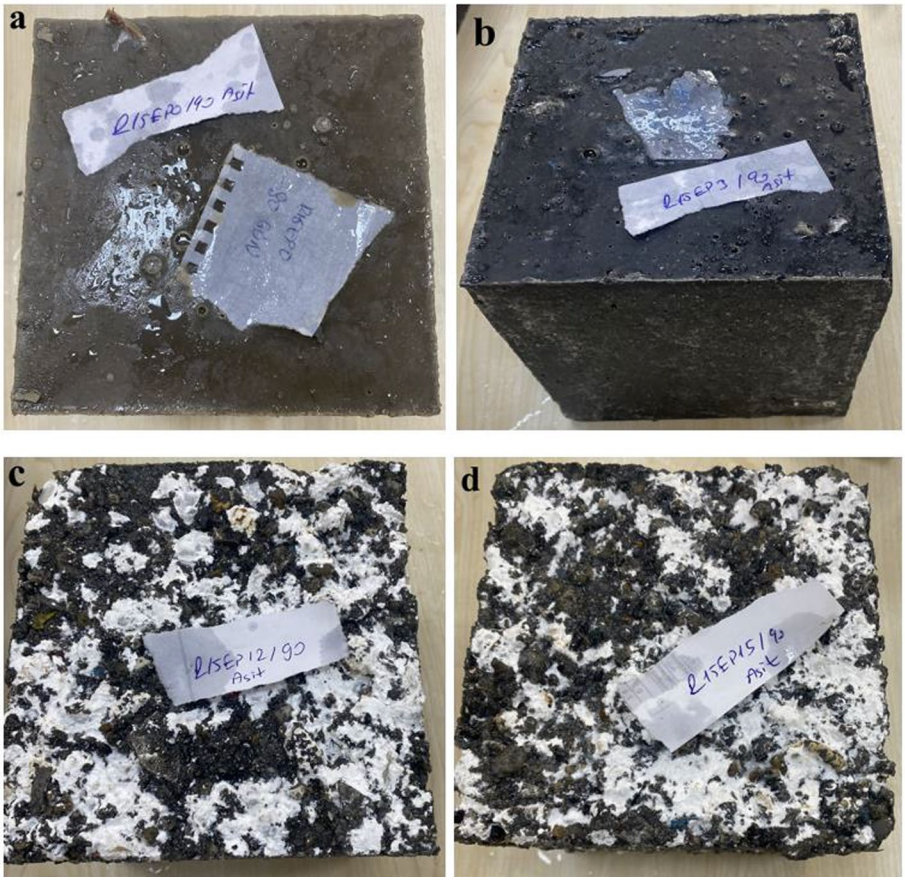


Fig. 16 Images of the polymer concretes exposed to an acid attack for 90 days, **a**: Control concrete (C/90), **b**: 3% e-waste polymer concrete (EW3/90), **c**: 12% e-waste polymer concrete (EW12/90), **d**: 15% e-waste polymer concrete (EW15/90)

3.8 Sulfate attack

The weight and compressive strength losses of the e-waste polymer concrete specimens after being subjected to a sulfate attack at early, middle and advanced ages (7, 28 and 90 days, respectively) and the analysis results obtained as a result of a visual evaluation are presented in this section.

3.8.1 Weight loss of sulfate attacked polymer concretes

The weight losses of polymer concrete specimens subjected to the sulfate attack for 7, 28 and 90 days are shown in Fig. 17.

Within all the groups and on the basis of all the measurement days, the concrete specimens with the highest resistance to the sulfate attack and the lowest weight loss were the polymer concrete specimens produced using 3% e-waste. For example, while the weight loss of the control concrete (C/7) was 0.07% after 7 days of the sulfate attack, this loss was 43% less and realized as 0.04% in the polymer concrete with 3% e-waste (EW3/7). As the e-waste ratio and day duration increased, increases in the weight losses were also observed. A similar observation was reported in one of the few studies found in the literature [104]. Although increases in weight losses were obtained as a result of the sulfate attack, it can be clearly seen in Fig. 17 that these losses were realized at low levels. It can be concluded that polymer concrete using e-waste as an aggregate can be used effectively against a key durability problem, such as a sulfate attack.

When evaluated in general, the e-waste polymer concrete specimens experienced a (negligible) weight loss value close to 0 after the sulfate attack, which causes high levels of destruction and deterioration of concrete structures;

- Unlike traditional concrete, polymer concrete does not contain any water or cement, so sulfate-resistant concrete can be produced without any chemical reaction of sulfate ions that would disrupt the integrity of the concrete or cause it to expand.

- The high compatibility of plastic-based e-waste with resins brings with it strong adherence, enabling the production of strong polymer concrete with aggregate-matrix interfaces that are sensitive to sulfate attacks.

3.8.2 Compressive strength loss of sulfate attacked polymer concretes

Figure 18 shows the compressive strength losses of the polymer concrete specimens exposed to a sulfate attack on different days. Similar to the weight losses, the concrete with the lowest compressive strength loss among all the groups

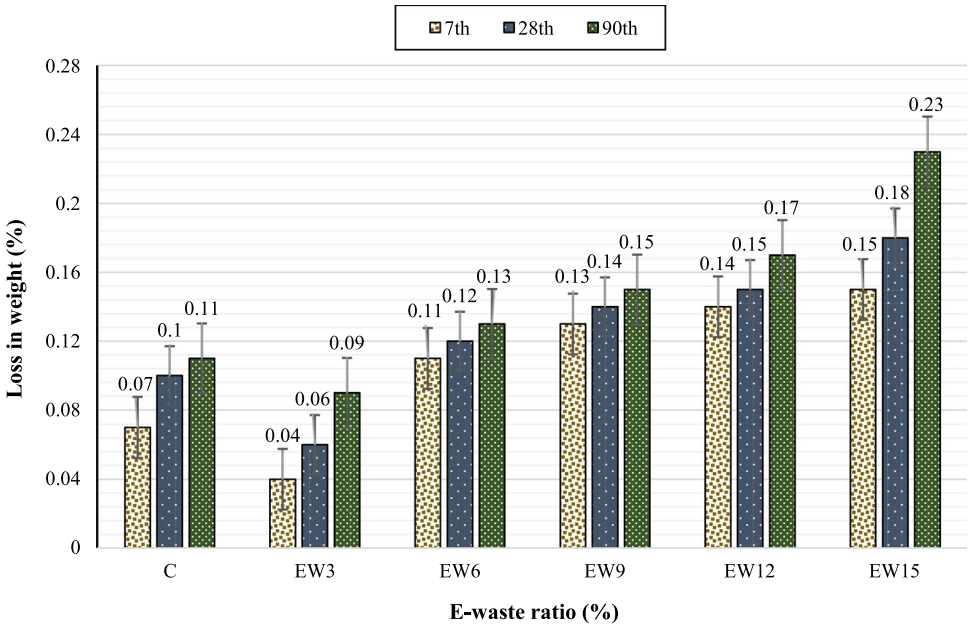


Fig. 17 Loss in weight of the sulfate attacked polymer concretes

was the polymer concrete with 3% e-waste. Evaluating the 28-day results, for example, while the compressive strength loss of the control concrete (C/28) was 4.16%, this loss decreased by 23% to 3.22% in the polymer concrete with 3% e-waste (EW3/28).

When the e-waste ratio increased to 15% (EW15/28), the compressive strength loss increased to 12.26%. The results for 7 and 90 days showed a similar trend. As the duration increased, the compressive strength loss due to the sulfate attack also increased. In another study using e-plastics in normal concrete, it was reported that concrete immersed in a sulfate solution for 90 days experienced strength losses of up to 37% [105]. In this study, even in the polymer concrete with 15% e-waste (EW15/90), which is the highest e-waste ratio, the compressive strength loss after the sulfate attack at the end of 90 days was 14.46%, approximately 50% less than the result of the study in the literature [105]. This case clearly shows the large difference between the resistance of traditional concrete and e-waste polymer concrete against sulfate attacks.

It is considered that the increase in the e-waste ratio facilitates the diffusion of sulfate ions, especially through more voids at the aggregate-polymer matrix interface, and these ions reduce the strength of polymer concrete by adversely

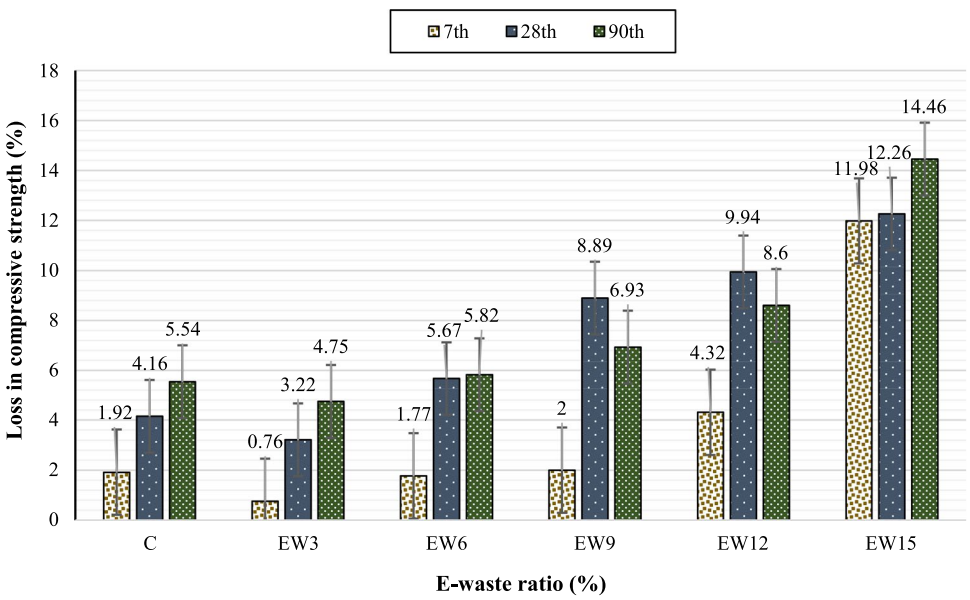


Fig. 18 Loss in compressive strength of the sulfate attacked polymer concretes

affecting adhesion and by forming microcracks [106]. In conclusion, this study has shown that 3% e-waste can be used as aggregate in polymer concrete to produce concrete that is resistant to sulfate attacks. It is thought that the superior adherence of the materials forming the polymer concrete with a 3% e-waste ratio is effective in this situation, similarly to the acid attack results.

3.8.3 Visual evaluation results of sulfate attacked polymer concretes

The images of the polymer concrete specimens after exposure to a sulfate attack for 90 days are given in Fig. 19. In parallel with the results of the visual analysis obtained after the acid attack, the polymer concrete least affected by the sulfate attack was the polymer concrete (EW3/90) in which 3% e-waste was used as an aggregate. This result can be clearly seen in Fig. 19 b. The polymer concrete specimens with 12% and 15% e-waste showed significant damage after the sulfate attack. As can be seen in Fig. 19 c and d, these damages were realized in the form of surface deterioration starting from the corners and edges, capping, exfoliation, aggregate-polymer matrix separation and peeling. The visual analysis results confirmed the weight and compressive strength losses of the polymer concrete specimens after the sulfate attack. The least damage was 3% and the most damage was observed in the 12% and 15% e-waste polymer concrete specimens.

4 Conclusion

In line with the results obtained from a detailed experimental study, it was revealed that the polymer concrete specimens with 3%, 6% and 9% e-waste, together with the control concrete, can produce polymer concrete with high strength by reaching 50 MPa and above on all the measurement days. While there was a clear increase in the duration of curing on the UPV results from 7 to 28 days, this was not realized as a significant increase from 28 to 90 days. The highest dynamic modulus of elasticity results were observed in the 3% e-waste added polymer concrete. The use of e-waste, especially up to 9%, showed that polymer concrete with capillary water absorption coefficient values close to those of the control concrete can be produced after 90 days. The increase in the e-waste ratio had little effect on the rapid chloride permeability values and all the values were negligibly low. It can be easily stated that concrete with a high

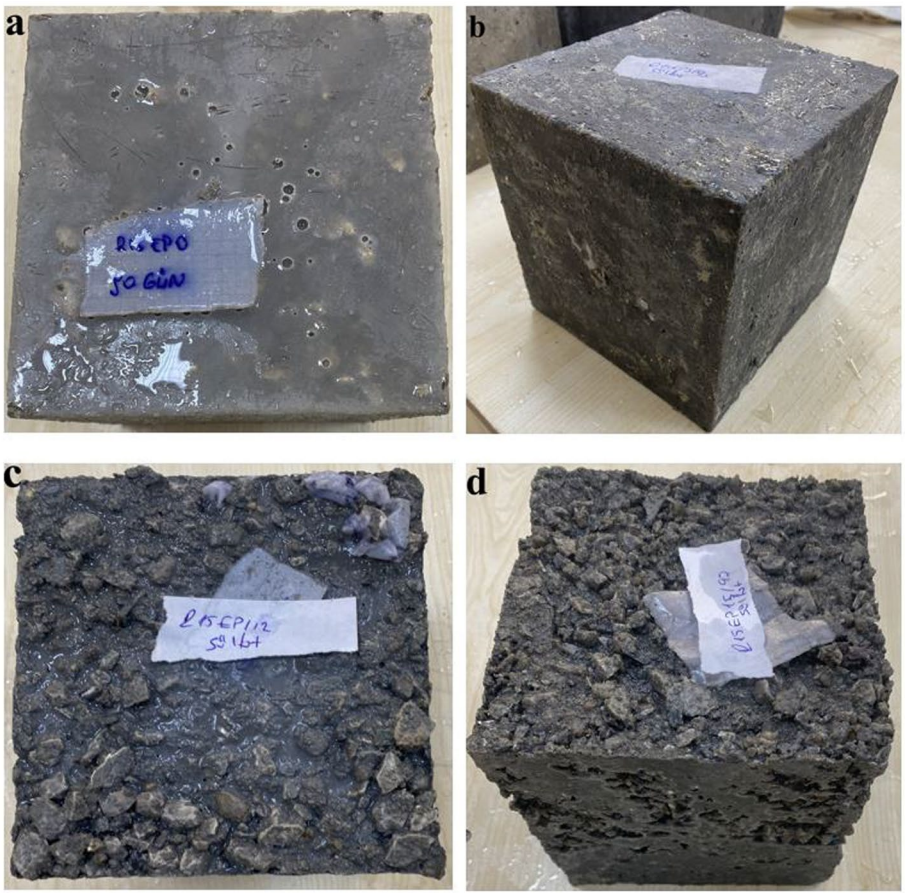


Fig. 19 Images of the polymer concretes exposed to the sulfate attack for 90 days, **a**: Control concrete (C/90), **b**: 3% e-waste polymer concrete (EW3/90), **c**: 12% e-waste polymer concrete (EW12/90), **d**: 15% e-waste polymer concrete (EW15/90)

resistance to acid and sulfate can be produced when e-waste is used as an aggregate in polymer concrete at 3%, 6% and 9% (compared to the control concrete). As a result of the study, a 3% e-waste ratio was found to be the ideal ratio for all the performed experiments. In a period when aggregate resources are decreasing and environmental pollution is increasing, it is thought that with this study, e-waste polymer concrete will fill an important gap in the literature in terms of the concept of sustainable concrete.

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Data availability The raw/processed data required to reproduce these findings cannot be shared at this time as the data also form as part of an ongoing study.

Declarations

Conflict of interest The authors have no conflicts of interest to declare. All co-authors have seen and agreed with the contents of the manuscript.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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