CHALLENGE JOURNAL OF CONCRETE RESEARCH LETTERS 15 (3) (2024) 69–81

Challenge Journal of Concrete Research Letters

Research Article

A different approach for green concrete production: Determination of the effect of e-waste and waste rubber powder on durability properties of concrete

H. Alperen Bulut [a,*]

[a] *Department of Civil Engineering, Erzincan Binali Yıldırım University, 24002 Erzincan, Türkiye*

ABSTRACT

This study was carried out to present a different approach to green concrete production by utilizing electronic waste (e-waste) and waste rubber powders in order to provide a solution to both the cost and carbon footprint problems arising from the rapid consumption of aggregate resources and cement. For this purpose, 0%, 5% and 10% of e-waste was utilized instead of aggregate and 0%, 2.5% and 5% of waste rubber powder was utilized instead of cement. In addition, mixtures in which both wastes were combined in concrete were also prepared and comparisons were conducted. Capillary water absorption, acid and sulfate attack tests were carried out on the concretes with different wastes at the end of 28 and 90 days. The capillary water absorption of concrete produced with 5% waste rubber powder at the end of 28 days (P5E0/28) was 80% less than the control concrete (C/28) (these values were 0.46, 2.36 respectively). It was determined that the utilization of waste rubber powder had a decreasing effect on the compressive strength losses of the concretes after acid attack compared to the control concrete, while e-waste had an increasing effect. It was determined that the compressive strength losses of the concretes in which waste rubber powder and e-waste were combined against sulfate attack were positively differentiated from both control concrete and concretes produced with single waste type. In parallel with the weight and compressive strength losses obtained after acid and sulfate attack, the results of the visual analyses of the concretes were similar. The use of 5% waste rubber powder in the concrete produced the greatest results. In addition, the ideal ratio between concretes in which e-waste and waste rubber powder used together was determined as 5% waste rubber powder and 5% e-waste. The results verified that e-waste and waste rubber powder can be considered for the production of green concrete.

ARTICLE INFO

Article history:
Received 21 February 2024
Revised 10 April 2024
Accepted 25 April 2024

Keywords:
Green concrete
E-waste
Waste rubber powder
Capillary water absorption
Acid attack
Sulfate attack

1. Introduction

As a result of the rapid advancement of technology and the unregulated disposal of electronic devices (e.g. photocopiers, computers, televisions, printers, mobile phones, white goods, etc.) that can be produced at lower costs, a new type of waste called electronic waste (e-waste) has emerged (Kiddee et al. 2013; Farooq et al. 2019). The amount of e-waste among solid wastes is increasing day by day (Bhutta et al. 2011). For example, 44.7 million tonnes of e-waste was reported worldwide in 2016 (Hameed et al. 2020). The rate of recycled e-waste is only 12.5% and the rest is either discarded or incinerated (Ullah et al. 2022). Direct disposal of e-waste, which contains composite materials in the structure, is not feasible, thus posing significant damage to both the environment and health worldwide (Partheeban et al. 2021). This situation has enabled the utilization of e-waste as a potential material in construction practices.

---

* *Corresponding author*. Tel.: +90-446-224-0088 ; E-mail address: habulut@erzincan.edu.tr (H. A. Bulut)

ISSN: 2548-0928 / DOI: https://doi.org/10.20528/cjcrl.2024.03.001

Studies evaluating e-waste in concrete have started to increase rapidly in the literature. For example, improvements in the abrasion resistance of e-waste concretes have been reported (Ferreira et al. 2012). As a result of the study conducted by Gawatre et al. (2015), the ideal compressive strength was obtained with the utilization of 7.5% e-waste. In another study (Suchithra et al. 2015), it was determined that concrete produced with e-waste had high resistance to chloride attack. Compressive and splitting tensile strengths decreased as a result of e-waste utilization instead of fine aggregate in concrete (Alagusankareswari et al. 2016). As a result of the evaluation of e-waste as aggregate in polymer concretes, which is a special type of concrete, it was found that e-waste increased the ductility of polymer concretes, although mechanical properties decreased as the e-waste ratio increased (Bulut and Şahin 2017). As a result of the study carried out by Ullah et al. (2022), decreases in the compressive strength of e-waste added concretes were observed with the effect of high temperature.

Overall technological developments, industrialization, urbanization, and expansion of the construction sector due to the population growth have quickly presented humankind with unprecedented problems. One significant consequence of this is the increase in the amount of waste products (Canbaz et al. 2021; Şengel et al. 2022a). Utilizing waste materials in concrete structures is crucial for environmental cleanup and recycling (Karalar and Çavuşlu 2022). Waste tires generated by the rapidly developing automobile industry have demonstrated tremendous annual growth globally (Colette et al. 2023). In fact, statistics report that the amount of waste tires generated worldwide each year exceeds 1.5 billion (Qaidi et al. 2021). It is known that waste tires, which are intended to be destroyed by traditional disposal methods (storage, incineration, burial, etc.), both lead to environmental pollution and increase carbon emissions (Islam et al. 2023a). Thus, the disposal of waste tires in an environmentally friendly and economical way has gained urgency globally (Jurado et al. 2023). In recent years, the utilization of waste tires in civil engineering practices has become widespread (Jiang et al. 2019; Gao et al. 2024).

Many studies on rubberized concretes produced with waste rubbers are present in the literature. In a study, it was reported that compressive strength losses reached 20% when 20% waste rubber was incorporated into concrete (Youssf et al. 2020). Mechanical properties, durability and deformation of rubberized concretes were investigated (Xu et al. 2021), and it was determined that chloride permeability decreased (Thomas et al. 2016), while ductility (AbdelAleem and Hassan 2022; Şengel et al. 2022b), toughness (Bahtli and Ozbay 2021) and thermal conductivity increased (Ma et al. 2023) as a result of utilizing the proper rubber particles in concrete. Kandil and Bulut (2023) investigated the behavior of concretes containing different proportions of waste rubbers against acid and sulfate attack. As a result, it was stated that rubberized concretes with a water/cement ratio of 0.5 exhibited high resistance to acid and sulfate attack. It was also emphasized that 12% and 16% waste rubber ratios are ideal ratios. In addition, as a result of a study conducted by Bulut (2024), both splitting tensile strength and UPV (Ultrasonic pulse velocity) test results gave the best results as a result of using 2.5% waste rubber and 5% e-waste rates together in concrete.

This study was carried out to present a different approach to green concrete production by evaluating electronic waste (e-waste) and waste rubber powders in order to provide a solution to both cost and carbon footprint problems arising from the rapid consumption of aggregate resources and cement. For this purpose, 0%, 5% and 10% of e-waste was substituted for aggregate and 0%, 2.5% and 5% of waste rubber powder was substituted for cement in concrete. In addition, mixtures in which both wastes were combined in concrete were also prepared and comparisons were carried out. Capillary water absorption, acid and sulfate attack experiments were carried out on concretes with different wastes after 28 and 90 days. The novelty of the research, unlike the literature, is that the durability properties of concrete are examined at both normal and advanced ages by using e-waste instead of aggregate and waste rubber powder instead of cement in different proportions in concrete production. In addition, it was aimed to increase the originality of the study by using these two waste types together and evaluating their effect on the durability performance of concrete. Thus, the effects of both types of waste on concrete will be comprehensively evaluated and introduced to the literature.

2. Materials and Method

2.1. Materials

CEM I 42.5 R type Portland cement was employed as a binder material for concretes with different wastes. The properties of this cement are presented in Table 1. Within the scope of the study, 4/8 mm and 8/16 mm graded coarse aggregates of crushed stone origin and 0/2 mm and 2/4 mm graded natural river sand were utilized as fine aggregates. The specific gravity of coarse aggregates of crushed stone origin was 2.651 for 4/8 mm gradation and 2.675 for 8/16 mm gradation. The specific gravity of fine aggregates is 2.478. As a result of preliminary tests, aggregate grades of 0/2 = 35%, 2/4 = 20%, 4/8 = 25% and 8/16 = 20% were selected and sieve analysis was performed according to TS EN 933-1 (2012) and TS 802 (2016) standards.

Superplasticizer chemical additive material was employed in the study. Information about this material is provided in Table 2. E-waste from electronic devices such as mobile phones, printers, monitors and televisions were shredded to aggregate size in the factories of Exitcom Recycling Company (Kocaeli/TR) and substituted for crushed stone and river sand in concrete production. The specific gravity of e-waste is 1.290. The visual of e-waste is presented in Fig. 1.

Waste rubber powder, which was utilized instead of cement, was obtained from Cemer Company (İzmir/TR). The visual of the waste rubber powder is presented in Fig. 2. The grain size distribution of waste rubber powder is given in Fig. 3.

Table 1. Properties of CEM I 42.5 R type Portland cement.

Chemical Compositions (%)	
SiO_2	19.27
Al_2O_3	4.62
Fe_2O_3	3.23
CaO	63.05
MgO	2.43
SO_3	2.88
Na_2O	0.32
K_2O	0.70
Cl^-	0.01
Loss on ignition	2.79
Insoluble residue	0.70
Physical Characteristics	
Residue on a 32 micron sieve	7.34
Specific gravity	3.10
Specific surface (cm^2/g)	3432
Beginning of setting	2hrs-31min
End of setting	3hrs-27min
Volume expansion (mm)	1.0
Compressive strength (MPa)	
2nd day	27.9
28th day	53.6

Table 2. Properties of the superplasticizer (ViscoCrete SF-18).

Chemical base	Modified polycarboxylate based polymer
Appearance	Light brownish liquid
Density (at +20°C) (gr/cm^3)	1.10
pH value	3-7
Alkali content (w/w, %)	≤ 3
Soluble in water chloride ion content (by mass, %)	≤ 0.10
Freezing point	-10 °C

Fig. 1. Image of e-wastes.

Fig. 2. Image of waste rubber powders.

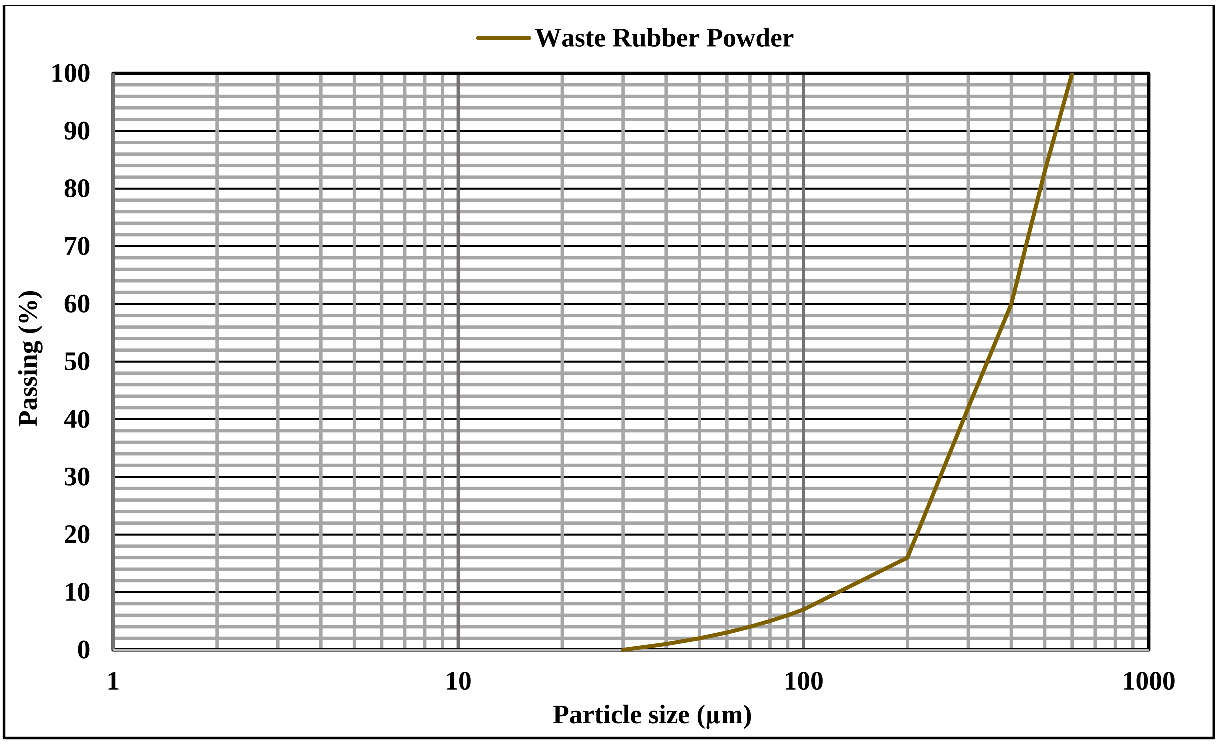

Fig. 3. Particle size distribution of waste rubber powder.

2.2. Parameters, coding and concrete mix design

The first parameter selected in this study is the different types of wastes and their proportions. In this context, 0%, 5% and 10% e-waste was utilized instead of aggregate and 0%, 2.5% and 5% by weight of waste rubber powder was utilized instead of cement. There was no waste type in the control concretes. The second parameter of the study was the comparison of capillary water absorption, acid and sulfate attack tests, which are the durability properties of concrete, at both 28 and 90 days. It is also considered that the single and combined utilization of both waste types in concrete is also a parameter for the study.

In the coding of the concretes, the abbreviations of the waste types (in English) are indicated by letters, the ratios are indicated by numbers, and the test days are indicated by numbers after the '/' sign. For example, P2.5E10/90 represents concrete containing 2.5% waste rubber powder and 10% e-waste and tested on day 90. Control concretes are indicated by the letter C. Water/cement ratio, cement dosage and superplasticizer ratio were constant at 0.45, 400 kg/m^3 and 1.8% respectively.

By using new generation superplasticizer chemical additives in concrete production, the slump values of concrete could be kept constant at 8 ± 1 cm. Considering that the slump value affects both the strength and durability properties of concrete (Moustafa and ElGawady 2015; Gesoglu et al. 2017; Helmy et al. 2023), it is considered that the properties of concrete to be examined in this study can be analyzed meaningfully by keeping the slump values constant thanks to the superplasticizer. Concrete mix design is presented in Table 3. In the coding in Table 3, the numbers representing the day of the experiments were excluded.

Table 3. Concrete mix design (kg/m^3).

Code	Cement	E-waste	Waste rubber powder	Fine agg.	Coarse agg.	Water
C	400			928.09	815.62	180
P2.5E0	390		10	927.62	814.51	180
P5E0	380		20	926.49	813.51	180
P0E5	400	43.92		881.69	774.85	180
P0E10	400	87.85		835.28	734.07	180
P2.5E5	390	43.92	10	871.33	742.38	180
P2.5E10	390	87.85	10	834.69	733.51	180
P5E5	380	43.92	20	853.22	724.56	180
P5E10	380	87.85	20	822.73	714.43	180

2.3. Methods

Experiments were carried out on concretes with different ratios of e-waste and waste rubber powder at the end of 28 and 90 days curing period. In order to carry out the dry weighing (W_0) of the concrete in the capillary water absorption test, the samples were dried in an oven (65±5 °C) for one day and cooled at ambient temperature. The concretes were placed in 5 cm contact with water (measured by the size of their surface area (F, cm^2), the mass increase was found by weighing the amount of water absorbed in 1-4-9-16-25-36-49-64-81 minutes (t, min). Capillary water absorption coefficients were calculated by the slope of the curve obtained from the square root of the amount of water absorbed from the unit area and the elapsed time. The calculated values were also confirmed by Eq. (1).

$$K = \frac{Q}{F.\sqrt{t}} \tag{1}$$

In Eq. (1), K; capillary water absorption coefficient, Q; amount of water absorption, F; denotes the surface area where the samples come into contact with water, and t denotes the time. Capillary water absorption experiments were performed on cube samples after 28 and 90 days. Acid and sulfate tests were carried out on two samples from each concrete that were immersed in 5% H_2SO_4 and 5% Na_2SO_4 solutions for 28 and 90 days. The names of these experiments, related standards and sample sizes are presented in Table 4.

3. Results and Discussion

3.1. Capillary water absorption

Capillary water absorption test results of concretes with different waste types and ratios are presented in Fig. 4.

Table 4. Experimental studies, related standards and sample sizes.

Type of the test	Standard	Sample size
Capillary water absorption	ASTM C 1585 (2020)	150x150 mm cube
Acid attack	ASTM C 267 (2020)	150x150 mm cube
Sulfate attack	ASTM C 1012 (2019)	150x150 mm cube

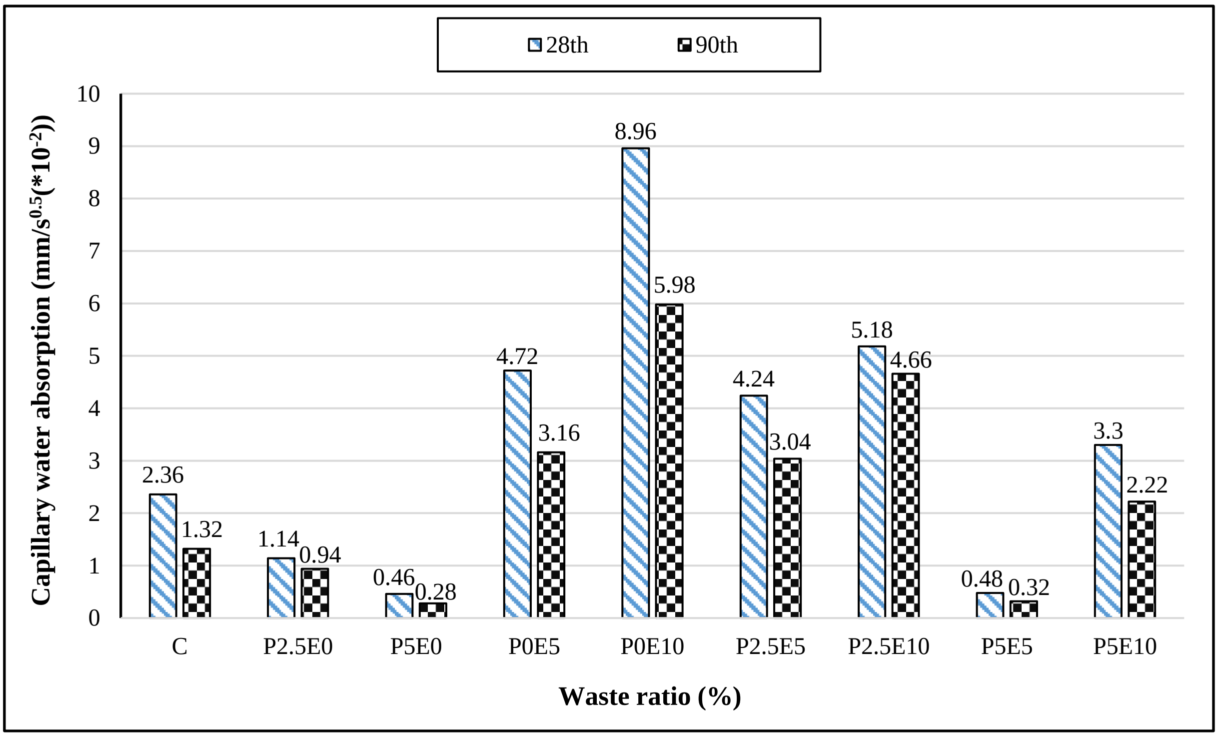

Fig. 4. Capillary water absorption results of concrete with different waste types and ratios.

Accordingly, the utilization of waste rubber powder in the concrete resulted in lower capillary water absorption values than the control concrete. For example, when the 28-day results are analyzed, while the capillary water absorption of the control concrete (C/28) was 2.36, this value decreased to 1.14 in concrete with 2.5% waste rubber powder (P2.5E0/28), and the capillary water absorption value decreased by 80% with a value of 0.46 in concrete produced with 5% waste rubber powder (P5E0/28). Similar situation was also observed in 90 days results. Similar behavior was also reported in studies on capillary water absorption properties of waste rubber concretes (Medine et al. 2018; Steyn et al. 2021).

Capillary water absorption values increased as a result of the utilization of different ratios of e-waste in concrete. For example, when the 90-day results were analyzed, capillary water absorption of 5% e-waste concrete (P0E5/90) was 3.16, while this value was 5.98 when the e-waste ratio increased to 10% (P0E10/90). At the end of 90 days, the capillary water absorption value of 10% e-waste concrete was 4.5 times higher than the control concrete and 21 times higher than the concrete with 5% waste rubber powder. It is believed that the porous structure of e-waste is effective in obtaining this result (Ahmad et al. 2023). Parameters such as air content, presence of chemical additives, number and type of voids, aggregate properties, curing time, and hydration time are believed to be effective on capillary water absorption values of concretes (Gesoğlu and Güneyisi 2011).

When the concretes in which waste rubber powder and e-waste were combined, it was observed that the best result was obtained in concretes containing 5% waste rubber powder and 5% e-waste. The capillary water absorption values of this concrete (P5E5) were quite low with 0.48 and 0.32 for 28 and 90 days respectively. In this situation; it is considered that e-waste is hydrophobic in nature and its low water absorption capacity is effective in producing concretes with low capillary water absorption coefficient by exhibiting strong compatibility when combined with 5% waste rubber powder in the presence of 5% e-waste ratio (Manjunath 2016; Ullah et al. 2021; Ahmad et al. 2022). Additionally, as a result of the limited studies on this subject in the literature (Pedro et al. 2013; Fadiel et al. 2014; Si et al. 2017), it has been reported similar to this study that rubber aggregates used at low rates (especially 5% and less) reduce the capillarity coefficients of concrete.

It was observed that capillary water absorption values decreased in all concretes as the curing time increased. This is attributed to the increase in cement hydration over time and to the fact that the water on the wastes reduces the air voids and prevents capillary water ingress (Islam et al. 2023b).

3.2. Acid attack

After 28 and 90 days of exposure to acid attack, weight loss, compressive strength loss and visual evaluations of waste rubber powder and e-waste concretes with different ratios were carried out comprehensively.

3.2.1. Weight loss of acid attacked concretes

The weight losses of the concretes after acid attack are presented in Fig. 5. The weight losses of the concretes after acid attack decreased as a result of the substitution of 2.5% and 5% waste rubber powder for cement. For example, when the 90-day results are analyzed, the weight loss of the control concrete (C/90) was 1.92%, while the weight loss of the concrete with 5% waste rubber powder (P5E0/90) was 0.42%. As observed during concrete production, other concrete components that are highly compatible with waste rubber powder exhibited superior workability, did not show any negative behavior such as crack formation or material separation in the concrete, and concretes with high resistance to acid attack could be produced (Kandil and Bulut 2023).

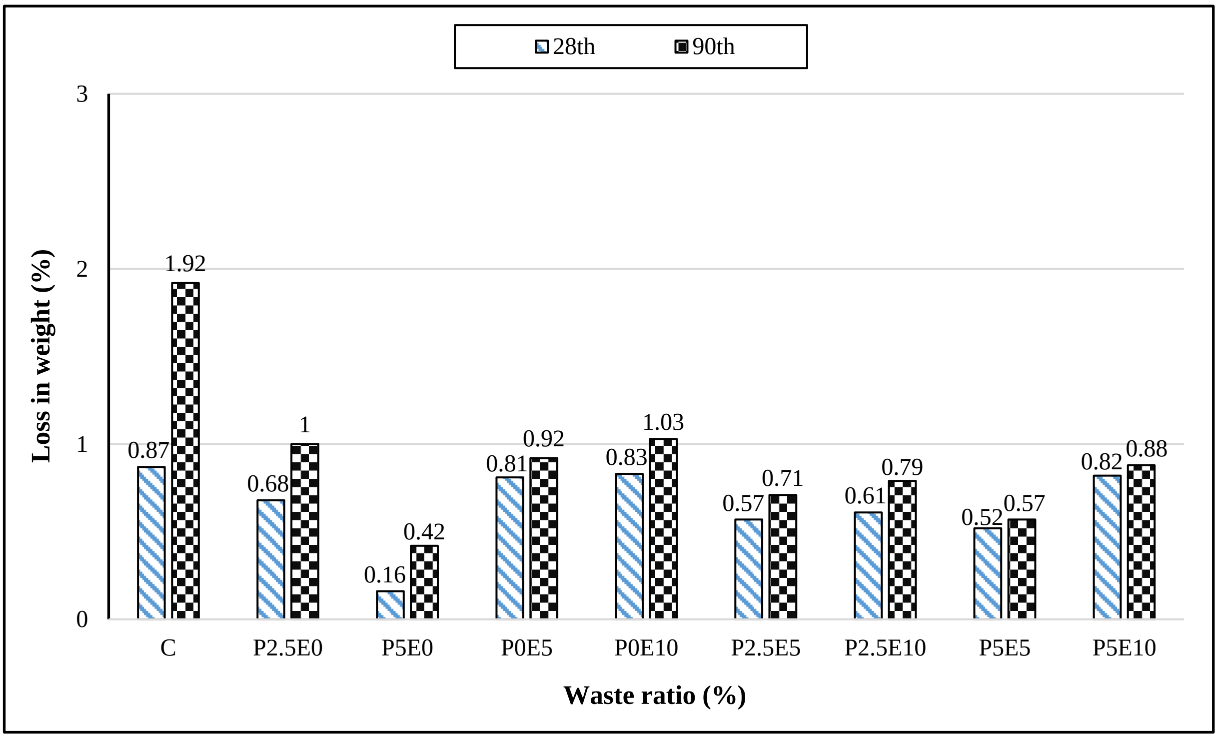

Fig. 5. Loss in weight results of concretes after acid attack.

When different ratios of e-waste were included in the concrete, weight losses were less than the control concrete. For example, the weight losses of concretes with 5% and 10% e-waste ratios after 28 days of acid exposure were 0.81% (P0E5/28) and 0.83% (P0E10/28), respectively. As a result of the combined utilization of both waste types in concrete, it was observed that the lowest weight loss was 0.52% and 0.57% in concretes containing 5% waste rubber powder and 5% e-waste (P5E5) after 28 and 90 days, respectively.

After 28 and 90 days of exposure to acid, the weight losses of concretes containing waste rubber powder and e-waste were lower than the control concrete. This indicates that more resistant concretes can be produced against acid attack by incorporating two waste types in concrete.

3.2.2. Compressive strength loss of acid attacked concretes

The compressive strengths of the concretes before and after acid and sulfate exposure were carried out according to TS EN 12390-3 (2019) standard and given in Table 5. Based on the results in Table 5, In Fig. 6, the compressive strength losses of concretes with different types and ratios after 28 and 90 days of exposure to acid attack are provided in percentages.

Table 5. Initial compressive strength results of concretes before acid and sulfate tests.

Code	28-day compressive strength (MPa)	90-day compressive strength (MPa)
C	41.10	44.50
P2.5E0	48.60	51.40
P5E0	44.00	48.40
P0E5	39.00	42.90
P0E10	19.20	23.40
P2.5E5	42.00	44.80
P2.5E10	24.50	28.80
P5E5	35.20	36.20
P5E10	29.30	32.00

According to Fig. 6, it is observed that the utilization of waste rubber powder has a decreasing effect on the compressive strength loss of concretes after acid attack compared to the control concrete, while e-waste has an increasing effect. For example, when the 28-day results are analyzed, while the compressive strength loss of the control concrete (C/28) was 16.06%, this loss decreased by 23% to 12.39% in concrete with 5% waste rubber powder (P5E0/28), and increased by 30% to 22.8% with 10% e-waste. The lowest compressive strength loss was observed for all days in concretes containing 5% waste rubber powder and 5% e-waste (P5E5).

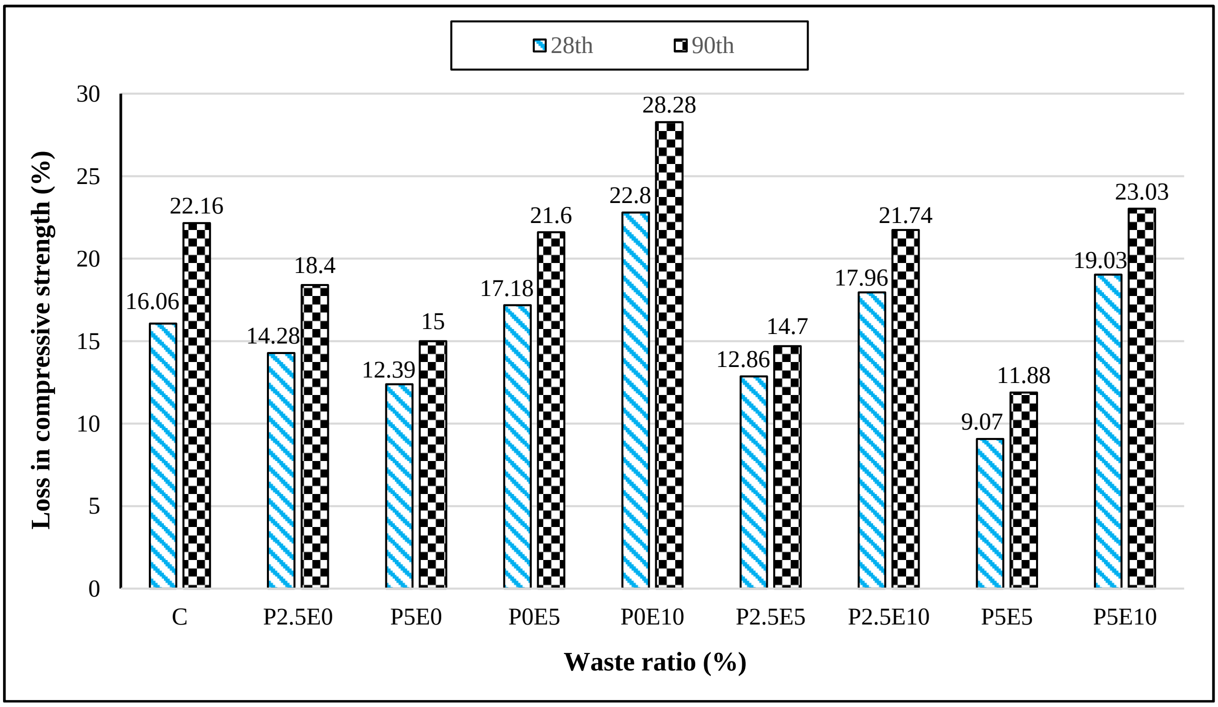

Fig. 6. Loss in compressive strength results of concretes after acid attack.

In general, compressive strength losses increased in all concrete groups after acid exposure from 28 days to 90 days. It is thought that the strength losses experienced by concretes after acid exposure may be due to the negative impact of the cement paste, especially as a result of long-term acid exposure, deterioration of the e-waste (aggregate)-matrix interface, and decreases in strength with the increase of microcracks (Kajorncheappunngam et al. 2002; Ghassemi and Toufigh 2020). As a result of the study, it can be stated that especially waste rubber powder can make concretes more resistant to acid attack. Considering that concretes containing 2.5% waste rubber powder-5% e-waste and 5% waste rubber powder-5% e-waste experienced less weight and compressive strength loss than the control concrete, it can be stated that they can be evaluated together in concretes that will be exposed to acid.

3.2.3. Visual evaluation results of acid attacked concretes

Fig. 7 presents the visual results of the concretes subjected to acid attack for 90 days. Accordingly, the visual damages of the specimens displayed a similar trend to the weight and compressive strength losses. It is clearly observed in a and b images that concrete with 5% waste rubber powder (P5E0/90) and concrete with 5% waste rubber powder-5% e-waste (P5E5/90), which are the concretes with the lowest weight and compressive strength losses, are visually more resistant to acid exposure. Control concrete (C/90) and concrete containing 10% e-waste (P0E10/90) suffered more visual damage (surface peeling, discolouration, abrasion, exfoliation) as a result of acid attack (visible in images c and d). This coincided with the weight and compressive strength losses.

Fig. 7. Images of concretes exposed to acid attack for 90 days:
(a) 5% waste rubber powder added concrete (P5E0/90);
(b) 5% waste rubber powder and 5% e-waste added concrete (P5E5/90);
(c) Control concrete (C/90); (d) 10% e-waste added concrete (P0E10/90).

3.3. Sulfate attack

Weight loss, compressive strength loss and visual evaluations of concretes containing waste rubber powder and e-waste subjected to sulfate attack on different days were analyzed in detail.

3.3.1. Weight loss of sulfate attacked concretes

Fig. 8 presents the weight losses of the concretes exposed to sulfate attack for 28 and 90 days.

The results obtained are remarkable and engaging for the literature and all of the concrete groups experienced weight increases instead of weight losses. For example, when the 90-day results were analyzed, the highest weight loss/increase was observed in concrete containing 5% waste rubber powder-10% e-waste (P5E10/90) and concrete containing 5% waste rubber powder-5% e-waste (P5E5/90) with values of -1% and -0.74%, respectively. When the sulfate attack increased from 28 days to 90 days, the weight increases in the concretes also increased. Sulfate attack is a complex mechanism with mechanical, chemical and physical processes and negatively affects the properties of concrete (Tanyildizi 2016; Ikumi et al. 2019). It is believed that sulfate ions blocked the pores of the concretes and caused an increase in weight. In addition, it is considered that the high absorption ability and deformation capacity of both waste types in the face of energy increase, which will reduce the entry and reactivity of sulfate ions into the internal structure, are effective in this situation (Onuaguluchi and Banthia 2019). It was determined that the weight losses/increases after the sulfate attack were similar to each other and very close to 0. This showed that concretes produced with waste rubber powder and e-waste can be resistant to sulfate attack.

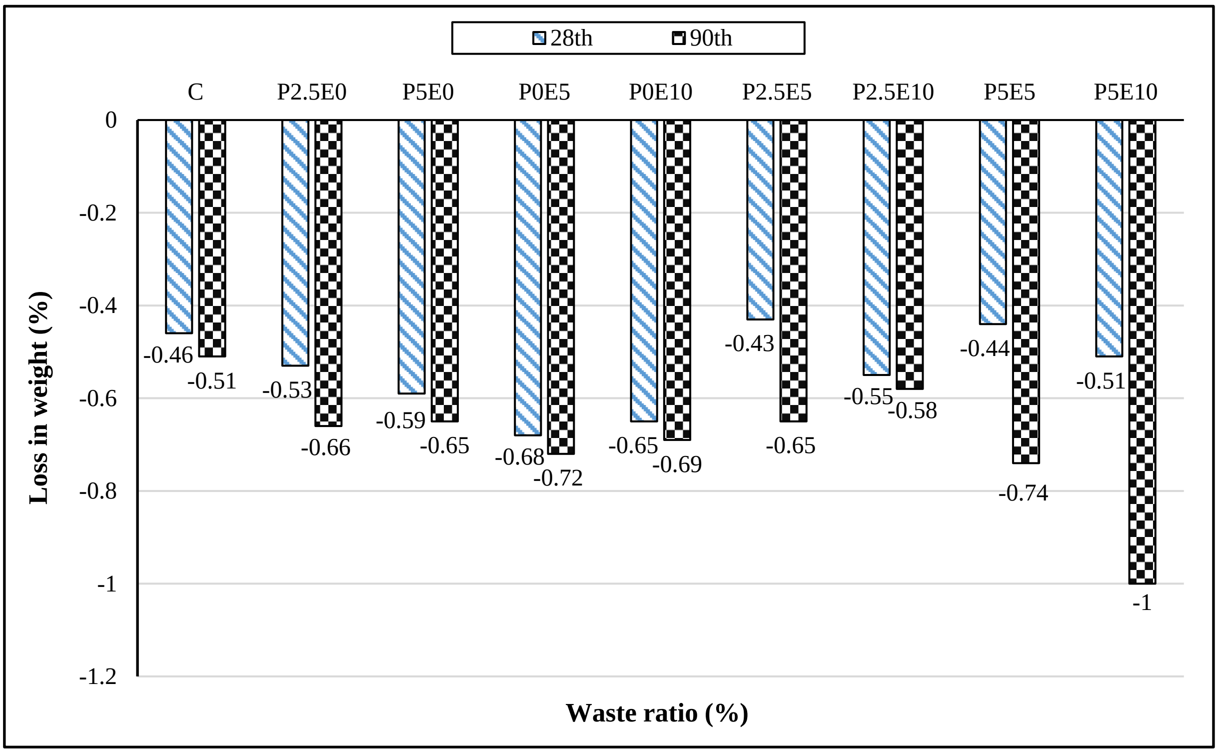

Fig. 8. Loss in weight results of concretes after sulfate attack.

3.3.2. Compressive strength loss of sulfate attacked concretes

Based on the results in Table 5, Fig. 9 illustrates the compressive strength losses due to sulfate attack depending on the day parameter on concretes with different proportions of waste rubber powder and e-waste.

From Fig. 9, it is clearly observed that the utilization of increasing proportions of waste rubber powder in concrete results in lower compressive strength loss after sulfate attack compared to the control concrete. For example, while the compressive strength loss experienced by the control concrete (C/28) after 28 days of sulfate attack was 6.81%, this loss decreased approximately 7 times less to 0.91% in concrete with 5% waste rubber powder (P5E0/28). The use of e-waste resulted in higher compressive strength losses. For example, after 90 days of sulfate attack, the compressive strength loss of 5% e-waste concrete (P0E5/90) was 13.84%, while the compressive strength loss of 10% e-waste concrete (P0E10/90) increased approximately 2 times to 25.39%. These two concretes had the highest compressive strength loss among all groups at the end of 90 days. It is considered that the strength losses of e-waste concretes after sulfate attack are affected by the fact that sulfate ions move more easily at the aggregate-matrix interface, which weakens and voids increase with the increase in ratio, negatively affecting the adherence and causing an increase in cracks (Griffiths and Ball 2000; Hashemi et al. 2018).

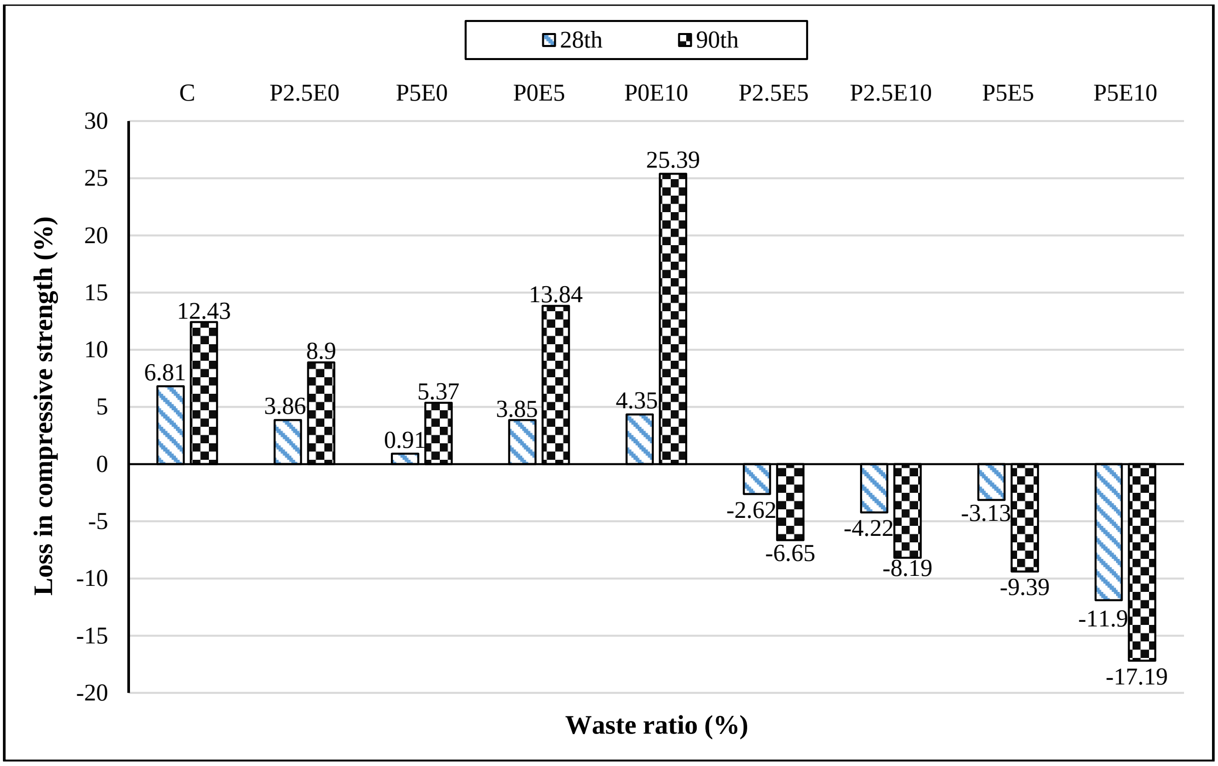

Fig. 9. Loss in compressive strength results of concretes after sulfate attack.

As a result of the combination of waste rubber powder and e-waste in concrete, interesting results were obtained for compressive strength losses after sulfate exposure. For example, at the end of 90 days, concrete containing 5% waste rubber powder and 5% e-waste (P5E5/90) and concrete containing 5% waste rubber powder and 10% e-waste (P5E10/90) did not lose compressive strength after sulfate attack, but on the contrary, their compressive strengths increased. These values were obtained as -9.39% and -17.19%, respectively. A similar pattern was observed in the concretes in which two waste types with lower ratios were combined. It was determined that the compressive strength losses of the concretes in which waste rubber powder and e-waste were utilized together against sulfate attack were positively differentiated from both control concrete and concretes produced using single waste type. For this study, it was determined that, with the ideality of the waste ratios, these expandable products can be applied to the walls of concrete voids, such as gypsum, ettringite and tomasite, which may occur due to sulfate attack in the internal structure of concretes produced by using both e-waste and waste rubber powder together at low rates. It is thought that the crystallization pressure is less and does not have a negative effect on the strength. (Scherer 2004).

3.3.3. Visual evaluation results of sulfate attacked concretes

Fig. 10 presents the visual results of concretes exposed to sulfate attack for 90 days. It was observed that 5% waste rubber powder-10% e-waste concrete (P5E10/90) and 5% waste rubber powder-5% e-waste concrete (P5E5/90), which differed from other concretes in a positive way in terms of both weight and compressive strength loss, did not suffer any significant damage after sulfate attack, as can be observed in a and b images. However, concrete with 5% e-waste (P0E5/90) and concrete with 10% e-waste (P0E10/90) were severely damaged after sulfate attack (chipping, peeling, cracking, discolouration at the corners) as can be clearly visualised in images c and d. The results of the visual analysis were similar to the weight and compressive strength losses obtained after sulfate attack.

4. Conclusions

The results obtained from this study, in which capillary water absorption, acid and sulfate attack experiments of concrete were carried out depending on the day parameter as a result of the utilization of e-wastes and waste rubber powder in concrete at different ratios, are summarized below:

- Capillary water absorption values of the concretes in which waste rubber powder was utilized instead of cement were lower than the control concrete. Capillary water absorption values of concretes produced using e-waste increased. At the end of 90 days, capillary water absorption value of 10% e-waste concrete was 4.5 times higher than control concrete and 21 times higher than 5% waste rubber powder concrete.
- The weight losses of concretes containing waste rubber powder and e-waste exposed to acid for 28 and 90 days were lower than the control concrete. It was determined that the utilisation of waste rubber pow-

der had a decreasing effect on the compressive strength losses of concretes after acid attack compared to control concrete, while e-waste had an increasing effect.

- All of the concrete groups exposed to sulfate attack experienced weight increases instead of weight losses. These increases were similar to each other and very close to 0. It was observed that the utilisation of increasing amounts of waste rubber powder in concrete resulted in lower compressive strength loss after sulfate attack compared to the control concrete. The use of e-waste resulted in higher compressive strength losses.
- In parallel with the weight and compressive strength losses obtained after acid and sulfate attack, the visual analysis results of the concretes were similar.
- When the test results are evaluated in general, the use of 5% waste rubber powder in concrete individually brought the best results. In addition, among the concretes in which e-waste and waste rubber powder were utilized together, the ideal ratios were determined as 5% waste rubber powder 5% e-waste.
- In terms of both the protection of natural resources and sustainability, it is significant for the literature to determine that waste rubber powder can be utilized instead of cement and e-waste can be substituted for aggregate in concrete production as a result of this study.

Fig. 10. Images of concretes exposed to sulfate attack for 90 days:
(a) 5% waste rubber powder and 10% e-waste added concrete (P5E10/90);
(b) 5% waste rubber powder and 5% e-waste added concrete (P5E5/90);
(c) 5% e-waste added concrete (P0E5/90); (d) 10% e-waste added concrete (P0E10/90).

Acknowledgements

None declared.

Funding

The author received no financial support for the research, authorship, and/or publication of this manuscript.

Conflict of Interest

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability

The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

REFERENCES

AbdelAleem BH, Hassan AAA (2022). Use of rubberized engineered cementitious composite in strengthening flexural concrete beams. *Engineering Structures*, 262, 114304.

Ahmad F, Qureshi MI, Ahmad Z (2022). Influence of nano graphite platelets on the behavior of concrete with E-waste plastic coarse aggregates. *Construction and Building Materials*, 316, 125980.

Ahmad Z, Alsulamy S, Raza A, Salmi A, Abid M, Deifalla AF, Khadimallah MA, Elhadi KM (2023). Life cycle assessment (LCA) of polypropylene fibers (PPF) on mechanical, durability, and microstructural efficiency of concrete incorporating electronic waste aggregates. *Case Studies in Construction Materials*, 18, e01979.

Alagusankareswari K, Kumar SS, Vignesh KB, Niyas AH (2016). An experimental study on e-waste concrete. *Indian Journal of Science and Technology*, 9(2), 1-5.

ASTM C 1585 (2020). Standard test method for measurement of rate of absorption of water by hydraulic-cement concretes. ASTM International, West Conshohocken, PA, USA.

ASTM C 267 (2020). Standard test methods for chemical resistance of mortars, grouts, and monolithic surfacings and polymer concretes. ASTM International, West Conshohocken, PA, USA.

ASTM C 1012 (2019). Standard test method for length change of hydraulic-cement mortars exposed to a sulfate solution. ASTM International, West Conshohocken, PA, USA.

Bahtli T, Ozbay N (2021). Mechanical properties and freeze-thaw resistances of bronze-concrete composites. *Challenge Journal of Concrete Research Letters*, 12(2), 39-48.

Bhutta MKS, Omar A, Yang X (2011). Electronic waste: A growing concern in today's environment. *Economics Research International*, 1-8.

Bulut HA, Şahin R (2017). A study on mechanical properties of polymer concrete containing electronic plastic waste. *Composite Structures*, 178, 50-62.

Bulut HA (2024). Evaluation of the impact of waste on the mechanical performance of concrete. *5th International Azerbaijan Congresses on Life, Engineering, Mathematical, and Applied Sciences*, Baku, Azerbaijan, 87-93.

Canbaz M, Kara İ, Topçu İ (2021). Effect of high temperature on the mechanical behavior of cement-bonded wood composite produced with wood waste. *Challenge Journal of Structural Mechanics*, 7(1), 42-48.

Colette DA, Martial AKD, Joseph AY, Benjamin YK, Patrick DA (2023). Optimization of the compressive strength of used tire/cement phase composite concretes using a full factorial design. *Construction and Building Materials*, 404, 133252.

Fadiel A, Al Rifaie F, Abu-Lebdeh T (2014). Use of crumb rubber to improve thermal efficiency of cement-based materials. *American Journal of Engineering and Applied Sciences*, 7(1), 1-11.

Farooq A, Abid MM, Tariq T, Riaz M, Haroon W, Malik AA, Rehman U (2019). Impact on concrete properties using e-plastic waste fine aggregates and silica fume. *Gospodarka Surowcami Mineralnymi - Mineral Resources Management*, 35(2), 103-118.

Ferreira L, Brito JD, Saikia N (2012). Influence of curing conditions on the mechanical performance of concrete containing recycled plastic aggregate. *Construction and Building Materials*, 36, 196-204.

Gao X, Yang J, Shao J, Zhu H, Xu J, Haruna SI (2024). Regulation of carbon nanotubes on internal humidity of concrete with recycled tire rubber: Mechanism analysis and modeling. *Journal of Building Engineering*, 82, 108253.

Gawatre D, Damal V, Londhe S, Mane A, Ghawate H (2015). Environmental issues of plastic waste use in concrete. *International Journal of Innovative Research in Advanced Engineering*, 2(5), 114-118.

Gesoglu M, Güneyisi E, Hansu O, Etli S, Alhassan M (2017). Mechanical and fracture characteristics of self-compacting concretes containing different percentage of plastic waste powder. *Construction and Building Materials*, 140, 562-569.

Gesoğlu M, Güneyisi E (2011). Permeability properties of self-compacting rubberized concretes. *Construction and Building Materials*, 25(8), 3319-3326.

Ghassemi P, Toufigh V (2020). Durability of epoxy polymer and ordinary cement concrete in aggressive environments. *Construction and Building Materials*, 234, 117887.

Griffiths R, Ball A (2000). An assessment of the properties and degradation behaviour of glass-fibre-reinforced polyester polymer concrete. *Composites Science and Technology*, 60(14), 2747-2753.

Hameed HB, Ali Y, Petrillo A (2020). Environmental risk assessment of E-waste in developing countries by using the modified-SIRA method. *Science of the Total Environment*, 733, 138525.

Hashemi MJ, Jamshidi M, Aghdam JH (2018). Investigating fracture mechanics and flexural properties of unsaturated polyester polymer concrete (UP-PC). *Construction and Building Materials*, 163,767-775.

Helmy SH, Tahwia AM, Mahdy MG, Elrahman MA (2023). Development and characterization of sustainable concrete incorporating a high volume of industrial waste materials. *Construction and Building Materials*, 365, 130160.

Ikumi T, Cavalaro SH, Segura I (2019). The role of porosity in external sulphate attack. *Cement and Concrete Composites*, 97, 1-12.

Islam MMU, Li J, Roychand R, Saberian M (2023a). Microstructure, thermal conductivity and carbonation resistance properties of sustainable structural lightweight concrete incorporating 100% coarser rubber particles. *Construction and Building Materials*, 408, 133658.

Islam MMU, Li J, Roychand R, Saberian M (2023b). Investigation of durability properties for structural lightweight concrete with discarded vehicle tire rubbers: A study for the complete replacement of conventional coarse aggregates. *Construction and Building Materials*, 369, 130634.

Kajorncheappunngam S, Gupta RK, GangaRao HVS (2002). Effect of aging environment on degradation of glass-reinforced epoxy. *Journal of Composites for Construction*, 6(1).

Kandil U, Bulut HA (2023). Examination of the permeability of rubberized concrete with different water/cement ratios and their resistance against acid and sulfate attack. *Progress in Rubber, Plastics and Recycling Technology*, Article In Press.

Karalar M, Çavuşlu M (2022). Evaluating effects of granulated glass on structural and seismic behavior of tall RC structures using experimental tests and 3D modeling. *Challenge Journal of Structural Mechanics*, 8(2), 63-77.

Jiang Z, Easa SM, Hu C, Zheng X (2019). Understanding damping performance and mechanism of crumb rubber and styrene-butadiene-styrene compound modified asphalts. *Construction and Building Materials*, 206, 151-159.

Jurado J, Zubiarrain NM, Villa EI, Rocco CG, Braun M (2023). Mesoscale modelling of the mechanical behaviour of concrete with rubber as coarse aggregate. *Engineering Fracture Mechanics*, 291, 109533.

Kiddee P, Naidu R, Wong MH (2013). Electronic waste management approaches: An overview. *Waste Management*, 33(5), 1237-1250.

Ma Q, Mao Z, Zhang J, Du G, Li Y (2023). Behavior evaluation of concrete made with waste rubber and waste glass after elevated temperatures. *Journal of Building Engineering*, 78, 107639.

Manjunath BTA (2016). Partial replacement of e-plastic waste as coarse-aggregate in concrete. *Procedia Environmental Sciences*, 35, 731-739.

Medine M, Trouzine H, Aguiar JBD, Asroun A (2018). Durability properties of five years aged lightweight concretes containing rubber aggregates. *Periodica Polytechnica Civil Engineering*, 62(2), 386-397.

Moustafa A, ElGawady MA (2015). Mechanical properties of high strength concrete with scrap tire rubber. *Construction and Building Materials*, 93, 249-256.

Onuaguluchi O, Banthia N (2019). Long-term sulfate resistance of cementitious composites containing fine crumb rubber. *Cement and Concrete Composites*, 104, 103354.

Partheeban P, Kalaiyarrasi ARR, PB LN (2021). Performance evaluation of geopolymer concrete using E-waste and M-sand. *Research on Engineering Structures and Materials*, 7(2), 183-198.

Pedro D, De Brito J, Veiga R (2013). Mortars made with fine granulate from shredded tires. *Journal of Materials in Civil Engineering*, 25(4), 519-529.

Qaidi SMA, Dinkha YZ, Haido JH, Ali MH, Tayeh BA (2021). Engineering properties of sustainable green concrete incorporating eco-friendly aggregate of crumb rubber: A review. *Journal of Cleaner Production*, 324, 129251.

Scherer GW (2004). Stress from crystallization of salt. *Cement and Concrete Research*, 34(9), 1613-1624.

Si R, Guo S, Dai Q (2017). Durability performance of rubberized mortar and concrete with NaOH-solution treated rubber particles. *Construction and Building Materials*, 153, 496-505.

Steyn ZC, Babafemi AJ, Fataar H, Combrinck R (2021). Concrete containing waste recycled glass, plastic and rubber as sand replacement. *Construction and Building Materials*, 269, 121242.

Suchithra S, Manoj K, Indu VS (2015). Study on replacement of coarse aggregate by e-waste in concrete. *International Journal of Technical Research and Applications*, 3(4), 266-270.

Şengel H, Kınık K, Erol H, Canbaz M (2022a). Effect of waste steel tire wired concrete on the mechanical behavior under impact loading. Challenge Journal of Structural Mechanics, 8(4), 150-158.

Şengel H, Özgören A, Erol H, Canbaz M (202b). Mechanical behavior investigation of rubberized concrete barriers in impact load. Challenge Journal of Concrete Research Letters, 13(3), 93-100.

Tanyildizi H (2016). The investigation of microstructure and strength properties of lightweight mortar containing mineral admixtures exposed to sulfate attack. *Measurement*, 77, 143-154.

Thomas BS, Gupta RC, Panicker VJ (2016). Recycling of waste tire rubber as aggregate in concrete: durability-related performance. Journal of Cleaner Production, 112 (Part 1), 504-513.

TS EN 933-1 (2012). Tests for geometrical properties of aggregates part 1: Determination of particle size distribution sieving method. Turkish Standards Institution, Ankara, Turkey, (Turkish Codes).

TS 802 (2016). Design of concrete mixes. Turkish Standards Institution, Ankara, Turkey, (Turkish Codes).

TS EN 12390-3 (2019). Testing hardened concrete part 3: Compressive strength of test specimens. Turkish Standards Institution, Ankara, Turkey, (Turkish Codes).

Ullah Z, Qureshi MI, Ahmad A, Khan SU, Javaid MF (2021). An experimental study on the mechanical and durability properties assessment of E-waste concrete. *Journal of Building Engineering*, 38, 102177.

Ullah K, Qureshi MI, Ahmad A, Ullah Z (2022). Substitution potential of plastic fine aggregate in concrete for sustainable production. *Structures*, 35, 622-637.

Xu J, Niu X, Ma Q, Han Q (2021). Mechanical properties and damage analysis of rubber cement mortar mixed with ceramic waste aggregate based on acoustic emission monitoring technology. *Construction and Building Materials*, 309, 125084.

Youssf O, Mills JE, Benn T, Zhuge Y, Ma X, Roychand R, Gravina R (2020). Development of crumb rubber concrete for practical application in the residential construction sector – design and processing. *Construction and Building Materials*, 260, 119813.