Mechanical and Durability Properties of Mortars Incorporating Red Mud, Ground Granulated Blast Furnace Slag, and Electric Arc Furnace Dust

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Abstract: This research studies the properties of mortars incorporating waste materials including red mud (RM), ground granulated blast furnace slag (GGBFS), and electric arc furnace dust (EAFD). Ordinary Portland cement (OPC) was partially replaced with equal contents of RM, GGBFS, and EAFD at different ratios by weight (0, 5, 10, 15, 20, 30, 40, and 50%). Slump, compressive strength, splitting tensile strength, electrical resistivity, water absorption, resistance to freeze–thaw cycles, and durability under sodium sulphate and sulphuric acid attacks were investigated. Moreover, the microstructure of mortars cured in tap water and exposed to sulphuric acid was examined using scanning electron microscopy (SEM) and energy dispersive X-ray spectrometer (EDX). Cement replacement up to 20% led to a slight increase in compressive strength at 7, 28, and 120 days, while the results of durability tests showed that only up to 10% cement substitution could improve the durability of the mortar. A microstructural analysis showed that small waste grain portions in the matrix improved the whole mix density and the interfacial transition zone (ITZ) between aggregates and paste. The results of this study showed that there is an optimum replacement ratio of about 10%, beyond which the incorporation of these waste powders can cause degradation of concrete properties.

Keywords: mortar; red mud; electric arc furnace dust; ground granulated blast furnace slag; mechanical properties; durability; microstructure

1. Introduction

Concrete is considered the most commonly used building material, and every year approximately 3–3.8 tonnes of concrete per person are produced worldwide [1,2]. However, the pressures on the cement and concrete industries are increasing in order to reduce greenhouse gas emissions and prevent natural resource depletion [3,4]. In light of this, many researchers in the field of concrete have started to study the reduction in cement consumption by using waste and by-products in concrete production [5-9], particularly as a cement replacement. The use of supplementary cementitious materials (SCMs) such as partial replacement of cement in concrete production can improve concrete properties, including its ultimate strength, workability, and durability [10]. In most cases, SCMs are derived from by-products of various industries or natural pozzolans; therefore, their use can both improve concrete properties but also help tackle some of the environmental issues in the construction industry. Red mud (RM), ground granulated blast furnace slag (GGBFS), and electric arc furnace dust (EAFD), which are generated as unwanted outcomes.
of bauxite and steel refineries, can be highly advantageous for concrete production, as they are mainly composed of silica (SiO$_2$), aluminium oxide (Al$_2$O$_3$), ferric oxide (Fe$_2$O$_3$), and quicklime (CaO), respectively, making them potential pozzolans. In addition, their grain size distribution, specific surface area, and the shape of their grains can improve the hardened and fresh concrete properties if they are mixed with cement in optimum values.

The literature shows that the influence of RM on cement-based composites can be highly related to its chemical and physical properties and can change based on the alumina generation process. Although a difference between the compressive strength results at early ages can be seen in most works [11–15], it was shown that, at later ages, RM could improve the mechanical characteristics [16]. Besides, using a sufficient amount of RM can contribute to forming a denser structure with reduced total porosity and smaller pores [17]. On the contrary, RM most often degrades the fresh properties, as it has a noticeably larger specific surface area (around 20 times) compared to cement [18], due to the existence of porous cancrinite in its structure [19]. RM reduces the workability, increases the initial and final setting times due to the presence of aluminium and sodium hydroxide [12], and when used in high contents reduces the maximum temperature during the hydration process but does not considerably change the hydration process [20].

The dust of iron melting furnace is also a metal-rich by-product obtained in large quantities annually worldwide from the steel industry [21]. Some researchers reported that compositions with up to 5% EAFD have superior mechanical performance than the control mix [21–24]. If this replacement ratio increases to 15%, the compressive strength can fall by about 20% [24]. However, in later ages, concrete mixes made with more than 5% EAFD showed the same performance as the control mix [25], highlighting the significant delay in strength evolution when applying EAFD in the mix. In fact, the setting time is proportional to the EAFD content [26,27], and the initial and final setting times of concrete with 2% EFAD content are longer than concrete without EAFD. EAFD contains a large amount of zinc (Zn), which is reported to have an essential role in controlling the concrete’s setting time, due to the reactions of Zn main forms (zincite (ZnO) and franklinite (ZnFe$_2$O$_4$)) with cement hydrates [27].

During the process of making iron and steel, GGBFS is also generated, which is considered very valuable for the concrete industry. Most researchers reported that the incorporation of GGBFS in concrete production improves its mechanical and durability properties. GGBFS can even be used as a replacement of cement in high proportions if the initial strength is not relevant [28]. Generally, regardless of the strength gain of concrete incorporating high volumes of GGBFS at later ages, early-age mechanical properties are usually inversely correlated to the percentage of GGBFS in mixes. However, at later ages, even mixes produced with a high proportion of GGBFS show superior or similar mechanical and durability performance compared to control mixes [29,30]. In fact, the use of GGBFS in concrete can lead to the formation of smaller pores, which in turn increases the durability of concrete components when exposed to adverse environmental conditions [28]. In addition, Ca(OH)$_2$, which is considered a by-product of cement hydration and does not contribute to the strength gain process of concrete, can react with water and GGBFS to form more calcium silicate hydrate (CSH) gel and improve hardened properties [30].

2. Research Significance

The literature shows that green concrete production with the help of waste materials can be a suitable solution to partially address the problems associated with cement production and industrial waste dumping. In most cases, the application of at least 5% waste powder as cement replacement improved the overall performance of cementitious composites. Moreover, some researchers showed that the simultaneous use of different waste products in concrete could produce superior results compared to the application of just one waste [31–33]. However, investigation on recent studies reveals that the performance of mortars produced with iron and alumina industry waste (RM, GGBFS, and EAFD) as partial replacement of cement has not been studied. The difference in the grain
size distribution of OPC, RM, GGBFS, and EAFD can lead to fewer voids in the matrix and improve its durability and mechanical properties. Besides, while the application of RM and GGBFS in previous studies reduced the workability of fresh concrete, EAFD can be used to enhance the fresh properties. Therefore, in this study, RM, GGBFS, and EAFD powders were used as partial cement replacement with different replacement ratios of 0, 5, 10, 15, 20, 30, 40, and 50% to appraise the durability and mechanical properties of mortar mixes.

3. Experimental Work

3.1. Materials and Mortar Mixes

In this research, river sand, supplied by Maat Beton Paya, Type II cement (OPC) from Mashhad Cement Co., (Mashhad, Iran) and tap water were used to prepare eight mortar mixes. RM was collected from Jajarm Alumina plant (located in North Khorasan province, Iran), while GGBFS and EAFD were supplied by the Khorasan steel complex. The chemical properties of OPC, RM, GGBFS, and EAFD are provided in Table 1. The chemical analysis, using the X-ray fluorescence technique (XRF), indicated that RM contained about 23.8% ferric oxide (Fe$_2$O$_3$), 18.3% calcium oxide (CaO), and 16.9% alumina (Al$_2$O$_3$), while the main constituents of GGBFS and EAFD were CaO and Fe$_2$O$_3$, respectively. An X-ray diffractometer (Explored, GNR Corporation, Italy) was used to characterize the mineralogical composition of the materials. The mineralogical composition of RM, GGBFS, and EAFD is illustrated in Figure 1.

Table 1. Chemical composition of cementitious materials (assessed through XRF analysis).

| Compounds | Cement (wt.%) | RM (wt%) | GGBFS (wt%) | EAFD (wt%) |
|-----------|---------------|----------|-------------|------------|
| SiO$_2$   | 21.6          | 13.4     | 11.5        | 4.5        |
| Al$_2$O$_3$ | 4.3          | 16.9     | 2.8         | 0.3        |
| Fe$_2$O$_3$ | 3.1          | 23.8     | 7.1         | 53.3       |
| CaO       | 62.1          | 18.3     | 34.5        | 10.5       |
| SO$_3$    | 2.0           | 0.5      | 0.3         | 0.6        |
| MgO       | 2.6           | 1.8      | 22.2        | 4.0        |
| K$_2$O    | —             | 0.5      | 0.4         | 5.7        |
| MnO$_2$   | —             | 0.1      | 0.7         | 0.8        |
| Na$_2$O   | —             | 4.4      | 0.2         | 3.4        |
| ZnO       | —             | —        | 0.2         | 1.1        |
| PbO$_2$   | —             | —        | —           | —          |
| CdO       | —             | —        | —           | —          |
| NiO       | —             | —        | —           | —          |
| Cr$_2$O$_3$ | —           | —        | 0.1         | —          |
| L.O.I     | —             | 14.9     | 19.5        | 15.5       |
| TiO$_2$   | —             | 5.2      | 0.3         | 0.1        |
| BaO       | —             | —        | 0.2         | —          |
| V$_2$O$_5$ | —             | —        | —           | 0.1        |
| Cl        | —             | —        | —           | 0.1        |
| P$_2$O$_5$ | —             | 0.2      | —           | —          |
| C$_3$A    | 4.3           | —        | —           | —          |

Based on the XRD analysis, the main phase in RM and GGBFS is calcite, and for EAFD, it is alite. The particle size distribution (PSD) of the investigated powders was determined using a particle size analyser (Vasco3, Corduan, France). The PSD results of OPC, RM, GGBFS, and EAFD are indicated in Figure 2. As seen there, $D_{mean}$ for cement, RM, GGBFS, and EAFD is equal to 374, 564, 6754, and 1560 nm, respectively. The difference in the grain size distribution of the cementitious materials is an important parameter in mix design, and it can lead to the filling of voids in hardened concrete and improve its durability performance. A LEO 1450 scanning electron microscope (SEM), which worked at a voltage of 20 KV, was used to realize the physical and morphological properties of by-produce powders. The images taken from RM, GGBFS, and EAFD are presented in Figure 3, while Figure 4 represents the shape and colour of these powders.
RM, GGBFS, and EAFD is equal to 374, 564, 6754, and 1560 nm, respectively. The difference in the grain size distribution of the cementitious materials is an important parameter in mix design, and it can lead to the filling of voids in hardened concrete and improve its durability performance. A LEO 1450 scanning electron microscope (SEM), which worked at a voltage of 20 KV, was used to realize the physical and morphological properties of by-produce powders. The images taken from RM, GGBFS, and EAFD are presented in Figure 3, while Figure 4 represents the shape and colour of these powders.

Figure 1. XRD pattern of RM, GGBFS, and EAFD (from top to bottom).

Figure 2. Particle size distribution of RM, GGBFS, and EAFD.

As seen in Figure 3a, some RM particles are spherical, while others have smooth and dense surfaces with an irregular polygon shape. According to Figure 3b, the microstructure of GGBFS has a polygon-like irregular geometry, whereas Figure 3c shows that EAFD morphology is made of ultrafine, spherically shaped particles. Comparing the micrograph obtained from the waste powders used in this study and the SEM images taken by other researchers [11,12,17,21,34–39] shows that, in most cases, the morphology and shape of grains are similar regardless of the production method. Figure 5a–d represent energy-dispersive X-ray spectroscopy (EDX) testing of waste powders used in this study. As shown in Figure 5a, the principal peaks in RM are related to Ca, Fe, Al, Si, and Na, while traces of Ti, K, and Cl can be seen. Figure 5b shows that the principal peaks in GGBFS are associated with Ca, C, and Mg, and trace amounts for Fe, Si, and Al can be observed. According to
Figure 5c, in EAFD, the principal peak is related to Fe, and almost the same amounts of Mg, K, Ca, and Na are distinguishable, and trace amounts for Si and Cl. Figure 5d compares the atomic and weight percentages of each element of three waste powders.

The mortar mix proportion was designed by the volumetric method of ACI 211.1 [40]. Mortar mixes were produced containing various weight contents of waste powders (0, 5, 10, 15, 20, 30, 40, and 50%) so that, in each mix, OPC was replaced with equal weight contents of EAFD, GGBFS, and RM. The mortar mixes’ composition, slump, and density are shown in Table 2. The density of all the mixes were in the 2106–2165 range, and the slump ranged from 105 to 150 mm. In the specimens with 5% replacement ratio, slump and density were the same as those of the control specimen, while increasing the replacement ratio over 5% decreased the slump and density. The preparation of mixes was carried out in a 30 L mechanical mixer, and after mixing, specimens were cast in moulds (Figure 6a). All specimens were demoulded after 24 h and processed under saturated condition until testing time (Figure 6b shows the strength-testing machine). Curing of the specimens was carried out in containers with tap water at the temperature of $20 \pm 4^\circ C$. As shown in Table 2, Ctrl indicates the mixed composition of the control specimen in which no waste is used. R, G, and E in the naming of mixes number 2 to 8 stand for RM, GGBFS, and EAFD as cement replacements (equal weight contents of waste). The number after RGE is also an indicator of cement’s weight percentage that was replaced with waste powders. According to Table 2, all the mortar mixes were prepared at a fixed water-to-binder ratio of 0.64 ($w/b = 0.64$).
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![Image of waste materials comparison with EDX test](image)

Figure 5. (a) RM, (b) GGBFS, (c) EAFD, (d) Comparison of three waste materials used in the study with EDX test

Figure 5. EDX analysis of waste powders.
Table 2. Mix proportions of all mortars and their properties.

| No | Name   | Water (g) | Cement (g) | RM (g) | GGBFS (g) | EAFD (g) | Sand (g) | W/b | Slump (mm) | Density (kg/m³) |
|----|--------|-----------|------------|--------|-----------|----------|----------|-----|------------|-----------------|
| 1  | Ctrl   | 1800      | 2820       | 0      | 0         | 0        | 10,563  | 0.64| 150        | 2165            |
| 2  | RGE5   | 1800      | 2679       | 47     | 47        | 47       | 10,563  | 0.64| 150        | 2168            |
| 3  | RGE10  | 1800      | 2538       | 94     | 94        | 94       | 10,563  | 0.64| 145        | 2161            |
| 4  | RGE15  | 1800      | 2397       | 141    | 141       | 141      | 10,563  | 0.64| 140        | 2158            |
| 5  | RGE20  | 1800      | 2256       | 188    | 188       | 188      | 10,563  | 0.64| 135        | 2153            |
| 6  | RGE30  | 1800      | 1974       | 282    | 282       | 282      | 10,563  | 0.64| 130        | 2147            |
| 7  | RGE40  | 1800      | 1692       | 376    | 376       | 376      | 10,563  | 0.64| 115        | 2120            |
| 8  | RGE50  | 1800      | 1410       | 470    | 470       | 470      | 10,563  | 0.64| 105        | 2106            |

Figure 6. (a) Steel mould used to produce cubic samples; (b) the strength-testing machine.

3.2. Fresh and Hardened State Tests

The fresh properties were appraised with a slump test, while the compressive and splitting tensile strengths were measured to study the mechanical properties of all specimens. Moreover, durability properties were examined using freeze–thaw cycles, sodium sulphate attack, sulphuric acid attack, water absorption, and electrical resistivity. The test methods on fresh and hardened samples are summarized in Table 3. In this study, in order to investigate the effect of freeze–thaw cycles, 30 cycles were conducted. The specimens started the freeze–thaw cycles after 28 days of curing. Saturated specimens were placed at −20 °C for 12 h and then at +4 °C for another 12 h to freeze and thaw. Regarding sodium sulphate attack, the 50 mm cubic samples were prepared and placed in a tap water bath. After 28 days, three samples were moved to the bath containing 20% sodium sulphate solution, and three samples remained in the tap water bath. Finally, the compressive strength of all samples was compared at the age of 120 days. ASTM C267 [41] was also used to evaluate the compressive strength and weight loss of specimens in the presence of sulphuric acid (H₂SO₄). After 28 days of processing in the tap water bath, specimens were moved to a bath containing 25% sulphuric acid solution (w/w) and were subjected to sulphuric acid for 7 days.

Table 3. Details of tests performed on fresh and hardened specimens.

| Test                  | Testing Age (Days) | Type of Specimens              | Reference Test Method | Specific Information |
|-----------------------|--------------------|--------------------------------|-----------------------|----------------------|
| Slump                 | Fresh mortar       |                                | ASTM C143 [42]        |                      |
| Compressive strength  | 7, 28, 120         | Cube (50 mm)                   | ASTM C109 [43]        |                      |
| Splitting tensile     | 120                | Cylinder (50 × 100 mm)         | ASTM C496 [44]        |                      |
| Freeze–thaw cycle     | 28 (start of cycles)| Cube (50 mm)                  | ASTM C666 [45]        | After 30 cycles One cycle in a day Freezing: in 12 h Thawing:12 h |
4. Results and Discussion

4.1. Compressive Strength

Figure 7 illustrates a comparison between the compressive strength of all mixes at 7, 28, and 120 days. In there, compressive strength gradually increased for all mortar mixes, indicating continuous reactions over time [49], and the increased rate of compressive strength depends on the mortar’s age and cement replacement ratio. Based on the compressive strength results at 7 days, in comparison to the control mix, cement replacement up to 20% led to an increase in compressive strength of mortar mixes to the extent of 7–14%. Moreover, cement replacement at 30, 40, and 50% led to a 4, 25, and 31% reduction in compressive strength, respectively. After 28 days of curing, 5, 10, 15, and 20% cement replacement resulted in an increase of 11, 9, 7, and 5% in compressive strength, respectively, while cement replacement at 30, 40, and 50% resulted in a decrease of 12, 22, and 31%, respectively. At 120 days of age, 20, 12, and 6% increment in compressive strength were achieved due to cement replacement by 5, 10, and 15%, respectively, while the compressive strength of specimens with 20% cement replacement and specimens with no waste (control specimens) was the same. Moreover, 30, 40, and 50% cement replacement led to a reduction in compressive strength to the extent of 18, 25, and 36%, respectively.

![Figure 7. Compressive strengths at 7, 28, and 120 days.](image-url)

The results show that cement substitution with RM, GGBFS, and EAFD (equal amounts) up to 20% leads to a slight increase in compressive strength, which can be attributed to the filler effect and the latent pozzolanic reactivity of aforementioned by-product powders. The filler effect and the latent pozzolanic reactivity of EAFD have been confirmed in the study done by Fares et al. [27]. Nedunuri et al. [50] also reported that, for high replacement ratios, activation and the pozzolanic reactions of GGBFS could lead to higher strength in GGBFS_OPC systems. However, due to the low pozzolanic nature of
most SCMs, increasing the cement replacement ratio usually leads to a decrease in compressive strength. In fact, there is a limit for cement replacement with waste powders (20% in this study) after which the pozzolanic reactions slow down, and beyond that, additional waste content acts as an inert material. This is mostly because of the relationship between the cement content and the quantity of calcium hydroxide (Ca(OH)$_2$), which is essential for pozzolanic reactions, as well as the pozzolanicity of SCMs. In concrete specimens with high amounts of SCMs, the excess SCMs are deactivated and operate like an inert material, as shown by Du and Tan [51]. While studying the effect of waste glass powder (WGP) on concrete properties, they realized that, for more than 30% replacement of binder with WGP, any other pozzolanic reaction was not initiated, whereas 15% replacement resulted in maximum compressive strength.

4.2. Splitting Tensile Strength

The splitting tensile test results for various mixes are shown in Figure 8 (some images of samples after splitting tensile strength are also presented in Figure 9). Figure 10 also illustrates the relationship between concrete’s splitting tensile strength and its compressive strength at 120 days, highlighting a relatively high correlation coefficient for all specimens at about 0.82.

![Figure 8. Splitting tensile strength of specimens at 120 days.](image1)

| Mortar mixes | Tensile Strength (MPa) |
|--------------|-----------------------|
| Ctrl         | 2.44                  |
| RGE5         | 2.50                  |
| RGE10        | 2.30                  |
| RGE15        | 1.97                  |
| RGE20        | 1.86                  |
| RGE30        | 1.78                  |
| RGE40        | 1.40                  |
| RGE50        | 1.28                  |

For 5% cement replacement, the tensile strength of specimens increased slightly (2%), while for more than 5% ratios, it decreased as the waste content increased. Generally, slight improvements in tensile strength can be related to lower porosity and development of binder and the interfacial transition zone (ITZ) properties, as is noted in works by Aliabdo et al. [52] and Ghalehnovi et al. [16]. The smaller size of waste powder particles in comparison with cement grains leads to improved densification of ITZ. However, increasing
the waste content by more than 30% considerably decreased the tensile strength (by about 50%), which can be attributed to the pozzolanicity of the used waste powders. While GGBFS showed an acceptable performance in terms of pozzolanic reactions with cement hydration products in previous works, EAFD and RM could not increase the mechanical properties of concrete when used in high amounts. Therefore, as the same amount of EAFD, RM, and GGBFS were used in this study, GGBFS could not govern the pozzolanic reactions, especially in mixes with more than 15% cement replacement.

![Graph](image)

**Figure 10.** Relationship between the splitting tensile strength and compressive strength of all specimens.

### 4.3. Freeze–Thaw Resistance

One of the most critical durability properties of concrete is its resistance against degradation due to freeze–thaw cycles, especially in cold climates [53]. The compressive strength results of specimens exposed to freeze–thaw cycles and cured in tap water are compared in Figure 11. As shown there, for all mortar mixes, the compressive strength of specimens under freeze–thaw conditions was less than that of normal conditions. In addition, by increasing the cement replacement ratio by more than 5%, the durability against freeze–thaw cycles decreased. Many researchers have investigated the freeze–thaw resistance of concrete with different SCMs, and conflicting results have been reported considering the age test, number of cycles, cycle temperatures, and duration of cycles. For example, in the case of using GGBFS, while in some works, concrete samples made with pure cement showed superior performance [54], and in other research [55,56], samples made with GGBFS displayed higher resistance against freeze–thaw cycles.

![Graph](image)

**Figure 11.** Compressive strength of specimens at 28 days (tap water and freeze–thaw cycles).
When concrete is affected by freeze–thaw cycles, ice formation in capillary pores generates expansion stress, which can be released if entrained air is present [57–62]. So, improving the freeze–thaw resistance, reducing capillary pore volume, and inducing proper formation of entrained air are vital for concrete production [63]. It is worth noting that the structure of voids can govern ice formation and damage occurrence in the interlock between particles [64,65], and decrement in the capillary pore volume plays a significant role in increasing resistance to freezing and thawing [66–68]. As shown in Section 4.7, the control mix and the one with 5% cement replacement have less capillary pore volume than specimens containing 50% waste as cement replacement. As a result, specimens made with 50% waste powders have lower freeze–thaw resistance. Figure 12 shows the results of the water absorption test conducted on 50 mm cubic specimens at the age of 28 days, based on the ASTM C642 standard [47]. According to Figure 10, the 30 minutes’ water absorption for the specimens experiencing 30 freezing–thawing cycles was slightly higher than that of the specimens cured in tap water. The water absorption after 24 h of specimens with different ratios of cement replacement exposed to freeze–thaw cycles was higher than that of the specimens cured in tap water. Overall, by increasing the cement replacement ratio, the water absorption of specimens after 30 min and after 24 h increased.

![Water absorption test results](image)

**Figure 12.** Water absorption of specimens in tap water and exposed to freeze–thaw cycles, at 28 days.

### 4.4. Permeability and Water Absorption

Permeability is an important internal factor affecting concrete durability so that, by decreasing permeability, multiple properties of concrete such as resistance to harsh environments improve. Figure 13 shows the water absorption results, representing permeability, of this study. For all specimens, the water absorption at 30 min and 24 h slightly decreased by increasing age, which is related to the evolution of internal pores. After 28 days of curing, chemical reactions are still uncompleted, which leads to less connection of internal pores so that, by increasing the curing time, a finer pore structure in the cement paste is achieved [69,70].
According to Figure 13, at 28 days, the 30 min and 24 hours’ water absorption of specimens increased with increasing waste content. At 120 days of age, the water absorption of specimens with 5 and 10% replacement was similar to that of control samples, while for more than 10% replacement, the water absorption had a rising trend. So, it can be said that, for higher than 10% replacement ratios, an increment in interconnected pores and cavities is the main cause of the higher water absorption values. Madandoust et al. [71] and Koushkbaghi et al. [72] reported a similar behaviour. Generally, any decrease in permeability and water absorption can be mainly due to the pore structure modification effects of the wider grain size distribution of SCMs, especially in the interfacial transition zone (ITZ) [33]. However, in this study, increasing the RM content negatively affected the water absorption, as the existence of many pits and folds on the surface of deactivated RM grains results in higher water absorption capacity [14,16].

4.5. Electrical Resistivity

Concrete is considered a relatively non-conductive material, and the electrical conductivity in specimens is due to the presence of water in pores and cavities. Therefore, the lower the number of pores, the lower the electrical conductivity, so that electrical resistivity is higher. As shown in Figures 14 and 15, the electrical resistivity of specimens containing 5% waste was similar to that of the control mix at 7 days, while at 28 and 42 days, it increased by 4%. At 7 days of age, the electrical resistivity of specimens with 10, 15, 20, 30, 40, and 50% waste powders decreased by 12, 23, 25, 46, 58, and 62%, respectively. However, after 28 days of curing, these values, which show reduction in electrical resistivity compared to the control mix, decreased to 7, 12, 18, 28, 32, and 33%, respectively. Based on these results, cement replacement at more than 5% led to a decrease in electrical resistivity at different ages. In this study, an increase in the replacement ratio resulting in electrical resistivity degradation. Thus, in these mortar mixes, electrical conductivity and permeability are not the determinant factors for electrical resistivity. In fact, higher EAFD content in mortar mixes means higher heavy metal content so that higher conductivity can be justified, which causes less electrical resistivity; this hypothesis was confirmed by Lozano-Lunar et al. [70].

![Water absorption at 28 and 120 days (after 30 min and 24 h)](image-url)
**Figure 14.** Electrical resistivity of all mortar mixes at 7, 28, and 42 days.

**Figure 15.** Relative electrical resistivity at the ages of 7, 28, and 42 days.

### 4.6. Durability against Sulphate Attack

External sulphate resources can severely damage concrete due to sulphate attack, especially in the solution mode where sulphate ions can freely infiltrate the concrete specimens. Sodium sulphate attack on calcium hydroxide and calcium hydro aluminate generates compounds including calcium sulphate (plaster) and ettringite, accompanied by an increase in volume. Figure 16 shows the compressive strength of specimens after being placed in a 20% sodium sulphate solution. Higher values for specimens with 5 and 10% cement replacement with waste might be due to a filler effect and the latent pozzolanic reactivity of waste, which was explained in Section 4.1. Durability loss against sulphate attack increased in specimens with more than 10% cement replacement. The compressive strength reduction percentage of specimens at 120 days after being placed in 20% sodium sulphate solution is also shown in Figure 17. Similar to the trend at 28 days, it is evident that, by increasing the cement replacement, the compressive strength reduction increased. A greater decline in compressive strength of specimens containing waste powders than the control specimens (pure cement) can be attributed to the slow pozzolanic reactivity of the added SCMs.
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Figure 16. Compressive strength at 120 days (tap water and 20% sodium sulphate attack).

Figure 17. Compressive strength reduction percentage at 120 days (20% sodium sulphate).

4.7. Durability against Sulphuric Acid

Long-term chemical resistance of concrete structures is important for sustainable economies; cementitious materials with high acid resistance are essential to build or maintain critical infrastructures [73], considering that the adverse effects of acid attack is accompanied by socioeconomic losses that cost a huge amount of money worldwide [74]. In particular, to build and maintain sewer structures in which biogenic sulphuric acid attack is the main mechanism of destruction, concrete and mortar with high sulphuric acid resistance are required [75–77]. Due to the distinct nature of the existing anion in sulphuric acid (sulphate ion), the damage mechanism for this type of acid is different from that of other acids. Sulphuric acid reaction with hydrated cement paste components is presented in Equations (1) and (2). Following the sulphuric acid reaction with hydrated cement paste components, calcium sulphate (gypsum or plaster), the salt reacts with hydrated calcium aluminosulphates or not hydrated aluminosulphate components that are available in the hardened paste, producing ettringite. Equations (3)–(5) describe the sulphate attack. An increase in volume accompanies ettringite formation and consequently internal stress, which may cause micro-cracks or even large cracks and intensify sulphuric acid attack [78].

\[
\begin{align*}
H_2SO_4 + Ca(OH)_2 &\rightarrow CaSO_4 + 2H_2O \\
H_2SO_4 + CaO.SiO_2.2H_2O &\rightarrow CaSO_4 + Si(OH)_4 + H_2O \\
3CaO.Al_2O_3.CaSO_4.12H_2O + 2CaSO_4.2H_2O + 16H_2O &\rightarrow 3CaO.Al_2O_3.3CaSO_4.32H_2O \\
3CaO.Al_2O_3.Ca(OH)_2.12H_2O + 3CaSO_4.2H_2O + 13H_2O &\rightarrow 3CaO.Al_2O_3.3CaSO_4.32H_2O + Ca(OH)_2 \\
3CaO.Al_2O_3 + 3CaSO_4 + 32H_2O &\rightarrow 3CaO.Al_2O_3.3CaSO_4.32H_2O
\end{align*}
\]
Extensive investigations have been conducted in order to improve concrete durability in harsh acidic environments. Previous research recommended less use of cementitious materials due to the vulnerability of cement hydration products, such as lime crystals and C-S-H gel, against sulphuric acid. Due to the nature of pozzolanic reactions, using cement replacement materials leads to a reduction in lime content and improves concrete permeability. Thus, using cement replacement materials such as natural pozzolans and GGBFS can improve concrete durability in environments subjected to sulphuric acid. However, some researchers suggested that cement replacement materials can also negatively affect concrete durability. Physical properties, chemical compounds, fineness, and pozzolanic reactivity of SCMs, along with test conditions, can be the affecting factors for such a contradiction in research results. Compressive strength results of specimens in 25% sulphuric acid solution and tap water bath are compared in Figure 18.

The compressive strength of specimens with up to 20% cement replacement was similar to that of the control samples, while for more than 20% replacement ratios compressive strength decreased, and 50% replacement led to the lowest strength. Therefore, it can be noted that partial cement replacement with waste can either positively or negatively impact durability of concrete against sulphuric acid based on content, shape, and texture of waste particles [16]. As seen in Figure 18, the control mix had maximum strength against sulphuric acid with around 44% reduction in compressive strength, while specimen with 50% cement replacement had the lowest resistance against sulphuric acid, with about 57% reduction in compressive strength. It is considered that a reduction in permeability helps decrease acid penetration into the mortar mix, and as a result, resistance against acid attack will be improved [79,80]. In this study, there were more pores and cavities in the mortar with 50% cement replacement than in the control mix, so acid penetration into this mortar mix was higher, and consequently, its durability against acid attack, in terms of compressive strength loss, was lower.

Previous studies [81,82] on OPC-based binders showed that sulphuric acid has a deleterious effect on mass loss, which can be explained by the Ca(OH)$_2$ decomposition and gypsum formation that deteriorates the matrix by scaling and softening [79,81,82]. The weight reduction results of a sulphuric acid attack test are shown in Figure 19. Contrary to the results obtained for compressive strength loss, incorporating waste powders in mortar mixes improved their performance in terms of mass loss when exposed to acid attack. With 0, 5, 15, 20, 30, 40, and 50% replacement ratios, average mass reduction was equal to 7.30, 6.12, 5.53, 5.27, 4.72, 3.32, 2.13, and 2.80%, respectively.
With 0, 5, 15, 20, 30, 40, and 50% replacement ratios, average mass reduction was equal to 7.30, 6.12, 5.53, 5.27, 4.72, 3.32, 2.13, and 2.80%, respectively.

**Figure 19.** Weight loss percentage of all specimens after 7 days’ immersion in 25% sulphuric acid solution.

### 4.8. Microstructural Properties

As the physical properties of cementitious composites liaise with the microstructure of the hardened matrix, microstructural analysis can be useful for the prediction of properties of cement-based products [49]. Figure 20 shows the SEM images of broken mortar samples with 0, 5, and 50% waste at 120 days.

![SEM images of Ctrl (a), RGE5 (b), and RGE50 (c) mixes.](image)

Significant densification can be observed in the SEM images for the mortar mix made with 5% waste (Figure 20b), highlighting the filler effect of waste powders. However, as shown in Figure 20c, several micro-cracks developed in the mortar mix with 50% waste,
and larger voids are evident, which can be assumed as the main reason of the high water absorption values (Figure 13) [39,83]. Therefore, whereas application of a limited content of waste powders can lead to pore refinement, increasing the replacement ratio may degrade the microstructural properties. Figure 21 also shows the EDX spectrum of C-S-H paste obtained from the mortar mixes containing 0, 5, and 50% waste, respectively, with the main peaks associated with Ca and Si. As the concentration of calcium in the C-S-H gel indicates density and stability of cement products [84,85], it can be said that the C-S-H gel formation in the mortars with 0 and 5% waste was highly stable.

Figure 21. Cont.
Figure 21. EDX analysis of mortar mixes.

Figure 22 shows SEM images of specimens made with 0, 5, and 50% waste powders exposed to sulphuric acid. The images of the specimens that were processed in tap water are also shown in Figure 20. A relatively compact microstructure for specimens in tap water can be seen there, while specimens subjected to sulphuric acid became more porous. In addition, mortars with 0 and 5% replacement, in comparison with the mix with 50% waste powders, had more compact and less porous structures. Therefore, it can be said that microstructure disintegration, along with a noticeable strength loss, are consequences of lower inter-crystalline bond strength [86]. Using 5% waste as cement replacement decreased the porosity and increased the acid resistance in terms of strength loss and disintegration of the microstructure. For 0 and 5% replacement, as shown in Figure 22a,b, needle-like products, possibly ettringite, as described in previous studies [11,87,88], were well formed, whereas in the case of 50% replacement, needle-like products cannot be seen (Figure 22c), highlighting the low rate of reaction in these mortars. Luo et al. [11] reported that, by incrementing uncalcined RM in mortar mixes, the needle-like products’ content significantly decreased. In their study, specimens containing 30% RM had almost no needle-like products, but specimens with 15% calcined RM had a few ones attributed to the dilution effect of RM’s incorporation [89].
5. Conclusions

In the present study, the compressive strength, splitting tensile strength, electrical resistance, water absorption, resistance to freeze–thaw cycles, durability against magnesium sulphate and sulphuric acid attack, and microstructure of mortar mixes containing RM, GGBFS, and EAFD as partial replacement of OPC were investigated. OPC was partially replaced by RM, GGBFS, and EAFD at different weight percentages (0, 5, 10, 15, 20, 30, 40, and 50%). Based on the experimental results, the following conclusions can be drawn:

1. The slump of all the tested mixes ranged from 105 to 150 mm. In the specimens with 5% replacement ratio, slump was the same as that of the control specimen. However, increasing the replacement ratio over 5% resulted in the reduction in the slump;

2. Replacing cement by RM, GGBFS, and EAFD up to 20% led to an increase in compressive strength resulting from the filler effect and latent pozzolanic reactivity of the waste powders. However, specimens with waste content higher than 20% experienced lower compressive strength compared to the control specimen;

3. At 120 days of curing, the 30 min and 24 h water absorption test of specimens with 5 and 10% replacement showed the same results as that of control specimens. However, after passing the 10% replacement ratio, as the waste content increased, the water absorption followed the same trend, and the number of interconnected pores and water-saturated cavities rapidly multiplied, resulting in a higher water absorption capacity;

4. The electrical resistivity of the mix with 5% waste content is the same as that of the control mix, and by increasing the replacement ratio, it decreases. This can be attributed to the presence of high contents of heavy metals in the waste, which can considerably boost the conductivity;

5. By increasing the waste replacement ratio, the reduction in compressive strength as a result of sulphate attack escalated, while mixes with 10% replacement ratio had a higher compressive strength compared to that of the control mix. The higher reduction in compressive strength of specimens containing waste powders relative to the control specimen can be attributed to the slow pozzolanic reactivity of the waste powders;

6. As the replacement ratio increased, the reduction in compressive strength and weight of specimens as a result of sulphuric acid attack increased and reduced, respectively. Specimens made with 15% replacement ratio had the same compressive strength as the control specimens. The specimens were exposed to a sulphuric acid solution at an early age, meaning that waste powders did not have enough time to develop pozzolanic reactions. This can be the main reason for the higher compressive strength loss of all mixes made with waste powders;

7. Due to the filler effect of waste grains, improvement in the density of mortar mixes with low amounts of waste powders was observed in SEM images. In addition, 5% cement replaced with waste powders could improve the ITZ between aggregates and paste. However, increasing the replacement ratio degraded concrete properties as
the size of pores increased, and the volume of needle-like products (most probably ettringite, which is mainly responsible for concrete strength) decreased.

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