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Article

Impact of Partial Replacement of Cement with a Blend of Marble and Granite Waste Powder on Mortar

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Abstract: The purpose of this study is to examine the effects of partially replacing cement with a blend of marble waste powder (MWP) and granite waste powder (GWP) in mortar, with the goal of reducing the environmental harm caused by cement. The investigation included an analysis of the distinctive properties of the two waste powders individually, as well as initial tests with various ratios to determine the optimal combination that yields the highest strength. It was observed that a 50% MWP to 50% GWP blend produced the most substantial strength. Subsequently, the effect of partial replacement of cement with the blend of marble and granite waste powder (MGWP) at various increments of 5%, ranging from 0% to 30%, was evaluated by subjecting the mortar to numerous tests to assess its workability, physical, mechanical, durability, and microstructural properties. The analysis of the employed waste powders confirmed that the GWP can be classified as a natural pozzolan material belonging to Class N. As the proportion of MGWP increased, the workability of the mortar mixes decreased. However, incorporating MGWP up to 15% resulted in enhancements in bulk density, compression strength, and homogeneity, with the best performance observed at a 10% MGWP content. Microstructure analysis confirmed that the addition of MGWP enhanced the bonding of C–S–H and C–H, leading to a denser morphological structure in the mixes, particularly at a 10% MGWP content. The utilization of MGWP not only significantly reduced the carbon footprint associated with cement production but also fostered sustainability.

Keywords: granite powder; marble powder; fresh mortar properties; mechanical properties; microstructure; durability; sustainability

1. Introduction

The production of cement is a significant contributor to carbon dioxide (CO_2) emissions, primarily due to the calcination process. During calcination, limestone is heated at high temperatures to produce clinker, releasing CO_2 as a byproduct and contributing to greenhouse gas emissions. Additionally, the fuel used in the kiln, such as coal or natural gas, emits CO_2 when burned. It takes approximately 4.7 million BTUs of energy, equivalent to burning 200 kg of coal, to produce one ton of cement [1]. Consequently, nearly one ton of CO_2 is emitted into the atmosphere as a result of this energy consumption. With an annual cement production exceeding 4 billion tons, the industry is responsible for approximately 8% of global CO_2 emissions [2].

Addressing the issue of CO_2 emissions from the cement industry presents a significant challenge, yet there exist several feasible avenues to investigate. One such approach

involves incorporating waste materials that possess cementitious properties into cement production. This method offers numerous benefits that extend beyond the reduction of clinker content and associated carbon emissions. Through the utilization of waste materials, it is possible to reduce the need for conventional cement ingredients, leading to the preservation of valuable natural resources. Moreover, repurposing these waste materials that would otherwise end up in landfills fosters waste reduction and diversion, fostering more sustainable waste management practices. Over the last two decades, numerous studies have explored the incorporation of supplementary cementitious materials (SCMs) derived from various industrial and agricultural wastes [3–7].

According to Pappu et al. [8], the marble industries' revenue generation results in the annual production of approximately 200 million tons of waste powder/sludge known as marble processing residue or marble processing rejects (MPRs), which is generated worldwide. Marble production yields a significant amount of waste, ranging from 20% to 30% or even higher, attributed to factors such as irregular shape, smaller size, and cutting and polishing processes. The amount of waste generated varies based on factors such as the type of marble, quarrying techniques, and the processing methods employed. In some cases, the waste generated can reach as high as 60% of the total material processed [9]. Granite waste follows the same pattern, exhibiting significant amounts of byproducts during production, similar to marble waste.

In light of the environmental threat posed by the continuous exploitation of marble and granite waste, researchers have examined the potential of waste marble and granite powder, derived from processing plants, to partially replace cement in construction materials. Numerous studies have shown that incorporating marble waste powder (MWP) and granite waste powder (GWP) as partial cement replacements can enhance the mechanical properties of concrete and mortar [10–13]. According to research conducted by Kumar et al. [14], incorporating 10% of GWP by weight as a replacement for cement in normal concrete resulted in an increase in compressive strength from $35 \, \text{N/mm}^2$ to $48 \, \text{N/mm}^2$. Additionally, the tensile strength of the modified concrete rose from $2.4 \, \text{N/mm}^2$ to $3.6 \, \text{N/mm}^2$. Ghorbani et al. [12] explored the combined influence of GWP as a partial replacement of cement and magnetized water on the mechanical and durability properties of concrete specimens exposed to two aggressive environments: NaCl and H_2SO_4 solutions. The findings indicate that when higher quantities of GWP are used, the strength and durability performance of the specimens decrease. This can be attributed to a reduction in cement content and the development of a more porous microstructure, regardless of the type of water used.

Prokopski et al. [15] investigated the impact of incorporating granite dust into concrete. Their research demonstrated that the inclusion of granite dust in concrete resulted in an improvement in the average density of concrete as well as early strength of the material. However, the introduction of granite dust in the concrete mixture caused a decrease in water absorption by 32–38% and water penetration by 60–70%. Shamsabadi et al. [13] examined the impact of GWP in concrete. They observed that the workability of concrete is influenced by the inclusion of GWP, with higher substitution ratios resulting in more pronounced alterations. The incorporation of 5% GWP led to an increase in the density of concrete. However, when higher substitution ratios were used, the density of concrete decreased. Lezzerini et al. [16] conducted a study to investigate the impact of MWP as a partial replacement for cement on the mechanical performance of mortar. Their findings revealed that substituting cement with marble waste in mortars consistently led to a decrease in mechanical properties. However, even with this reduction, the values remained acceptable for many applications, particularly when the substitution rate was below 25%. In their research, Amin et al. [11] investigated the impact of MWP and GWP on the compressive strength of mortar when used as partial replacements for cement. The study found that MWP did not yield a substantial increase in the compressive strength of cement mortar, in contrast to GWP. The authors also emphasized the importance of further studying the effects of utilizing a combination of MWP and GWP with varying mixing proportions.

Although there have been various studies investigating the use of MWP and GWP as partial substitutes for cement, a clear consensus on their impact on concrete or mortar performance is challenging to establish. This is primarily due to the fact that the origin of the marble and granite powder varies, resulting in differing performance outcomes. Some researchers have observed a negative effect on concrete strength when utilizing MWP and GWP, while others have noted positive effects with the appropriate rate of substitution on different properties of concrete and mortar. Moreover, differences in the ingredients used across studies make it difficult to compare the effects of these waste materials as partial substitutes for cement. In addition, most studies have examined the impact of MWP and GWP as partial substitutes for cement in either mortar or concrete separately, with a primary focus on mechanical properties.

The primary aim of this research is to explore the effects of blending marble and granite waste powder (MGWP) in varying proportions as a partial substitute for cement in mortar. What sets this study apart from previous research is its comprehensive investigation of the impact of MGWP on multiple properties of mortar when used as a replacement for ordinary Portland cement (OPC). While earlier studies focused on limited factors, this work examines a wide range of parameters including workability, bulk density, compressive strength, homogeneity, surface attack resistance, water absorption, thermal decomposition, and mineralogical composition. Furthermore, this study holds significance and novelty due to the specific region in which it was conducted. As the properties of MWP and GWP are significantly influenced by their origin, no prior research has been undertaken on this specific topic within the region of study. Therefore, the findings of this research provide valuable insights into the potential use of MGWP as a partial replacement for cement in mortar and its impact on various mortar properties.

2. Materials and Methods

This section comprises the details of the materials employed in producing the mortar that contains MGWP. It includes the property tests conducted on each material, as well as the examination of fresh, hardened, and microstructural properties of MGWP-containing mortars. As the primary focus of this study is to examine the impact of MGWP on mortar properties, all pertinent tests, including those that characterize MGWP, are specifically presented in Section 2.3. Meanwhile, fundamental tests outlining the cement and fine aggregate are included in Section 2.1. Furthermore, Section 2.4 provides a comprehensive overview of the methodologies used to analyze the impact of using MGWP on the properties of hardened mortar.

2.1. Materials

2.1.1. Cement

The study utilized ordinary Portland cement (OPC), obtained from Derba MIDROC Cement PLC. It meets the requirements of Ethiopian Standard ES 1177 [17], which is based on EN 197:1 [18] Cement Part 1: composition, specifications, and conformity criteria for common cements. Specifically, it conforms to CEM I and has a strength class of 42.5N (EN 197-1, 2011).

2.1.2. Marble and Granite Waste Powder

The granite and marble waste were acquired from the Kokeb Paint and Marble Factory, which is situated in Bahir Dar, Ethiopia, and subjected to drying at a temperature of 110 °C (230 °F), following the guidelines of ASTM D2216 to eliminate moisture. The visual appearance of cement, granite waste powder (GWP), and marble waste powder (MWP) is presented in Figure 1. The MWP exhibits a whitish color, the GWP displays a grey color, and the cement appears dark gray.
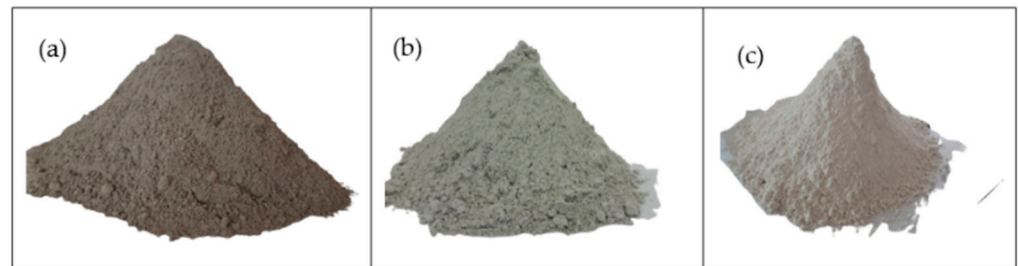
Figure 1. Visual characteristics of the employed cementitious materials (**a**) ordinary Portland cement (OPC), (**b**) granite waste powder (GWP), and (**c**) marble waste powder (MWP).

The outcomes of the X-ray fluorescence (XRF) analysis conducted on the OPC, MWP, and GWP utilized are compared in Table 1. The results of the test revealed that the specific surface area of GWP and MWP is almost five times higher than that of OPC. Regarding their chemical compositions, OPC and MWP had a relatively high and comparable concentration of CaO, specifically 64.31% and 52.28%, respectively. On the other hand, GWP mainly consists of oxides of SiO_2, with the highest proportion followed by Al_2O_3, accounting for 70.1% and 14.02%, respectively. The MWP exhibited a remarkably high loss of ignition (LOI), with a value of approximately 42% identified through analysis.

Table 1. Physical and chemical characteristics of OPC, MWP, and GWP.

Properties		OPC	GWP	MWP
Physical properties	Specific surface area	331 m^2/kg	1635 m^2/kg	1628 m^2/kg
	Color	Dark grey	Grey	White
	Oxides			
	CaO	64.31	3.96	52.28
	SiO_2	21.57	70.1	1.44
Chemical properties	Al_2O_3	5.73	14.02	0.01
	Fe_2O_3	3.48	1.84	0.01
	SO_3	1.2	–	–
	MgO	–	0.66	2.18
	K_2O	1.05	3.32	0.01
	LOI	1.5	1.72	41.59

According to the requirements outlined in ASTM C618, GWP can be categorized as a Class N natural pozzolan material, as it meets the conditions of having SiO_2 + Al_2O_3 + $Fe_2O_3 \geq 70\%$, CaO < 10%, and LOI < 10% [19]. However, according to the same standard, MWP does not fall under the classification of pozzolan material. The MgO content in GWP and MWP is 0.66% and 2.18%, respectively, and when combined, they remain under the 5% limit, signifying that they are appropriate for generating sound concrete [20].

2.1.3. Fine Aggregate

Impurity-free river sand from Lalibela, Ethiopia, was used as the source of fine aggregate. To confirm that its quality meets ASTM standards, the sand underwent several tests, and the results are presented in Table 2. The fine aggregate gradation curve from the sieve analysis test, as per ASTM C136 [21], is displayed in Figure 2. According to the gradation curve, the sand falls within the ASTM upper and lower limits. Moreover, other physical properties of the sand samples were evaluated, and their corresponding test results are presented in Table 2, with reference to their respective test standards.

Table 2. The test results of the physical properties of the fine aggregate.

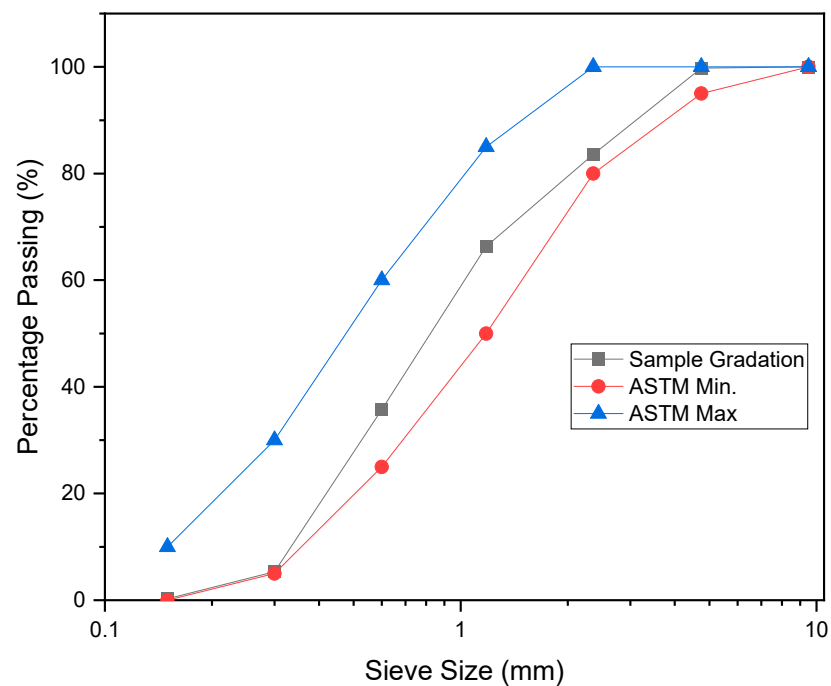| No	Test	Standard	Result	Unit
1	Fineness modulus	ASTM C33/C33M [22]	3.1	[–]
2	Specific gravity	ASTM C128 [23]	2.74	[–]
3	Water absorption	ASTM C128 [23]	3.09	[%]
4	Free moisture content	ASTM C566 [24]	2.1	[%]
5	Loose bulk density	ASTM C29/C29M [25]	1686.33	[kg/m^3]
6	Compacted bulk density	ASTM C29/C29M [25]	1870.5	[kg/m^3]
7	Voids	ASTM C29/C29M [25]	2	[%]
8	Silt content	ASTM C136 [21]	1.67	[%]

Figure 2. Gradation curve of the fine aggregate.

2.2. Mortar Mix Preparation

The initial phase of this study focuses on assessing the strength properties of mortar specimens by varying the replacement percentages of OPC with MGWP. These replacement percentages were 5%, 10%, 15%, 20%, 25%, and 30%, with ratios of marble and granite waste powder varying at 1:1, 1:2, and 2:1. Furthermore, a control mix was prepared, consisting only of OPC, with a consistent water-to-cement ratio of 0.51. The compressive strength test results indicated that the mortar specimens containing a 1:1 ratio of MWP and GWP exhibited the highest strength across all the replacement percentages considered. Consequently, mortar mixes utilizing a 1:1 MWP to GWP ratio were selected for further investigation. In Table 3, the codes assigned to each mixture of the finally considered mortar mixes are displayed. It also includes the corresponding proportions of OPC, MWP, and GWP used in each mixture.

Table 3. Proportions of OPC, MWP, and GWP used in the tested mortar mixes.

No.	Mix Code	Cement [%]	Marble [%]	Granite [%]
1	MGWP-0	100	0	0
2	MGWP-5	95	2.5	2.5
3	MGWP-10	90	5	5
4	MGWP-15	85	7.5	7.5
5	MGWP-20	80	10	10
6	MGWP-25	75	12.5	12.5
7	MGWP-30	70	15	15

2.3. Characterization of MGWP

2.3.1. Fourier Transform Infrared (FTIR) Analysis

The Fourier Transform Infrared (FTIR) technique was employed to assess the infrared radiation absorbance capacity of MGWP samples. The analyzed MGWP consists of a 1:1 ratio of MWP and GWP. The absorbance spectra of MGWP are plotted on a graph alongside OPC for the purpose of comparison. The absorbance band ranges from 4500 cm^{-1}–400 cm^{-1}. The formation band of alite is expected to be present at 980 cm^{-1} [26]. As seen in Figure 3, MGWP contains a higher amount of alite, which is advantageous for achieving high early strength. Bands corresponding to interstitial phases are observed in the range of 800 to 850 cm^{-1}. Sulfate minerals exhibit distinctive bands within the ranges of 3620 to 3200 cm^{-1}, 1600 to 1580 cm^{-1}, and 1300 to 1060 cm^{-1}. Additionally, calcium carbonate shows characteristic bands between 1580 and 1320 cm^{-1}, while calcium hydroxide displays a distinctive band at 3645 cm^{-1} [27]. The absorbance of tricalcium silicate (C_3S) is typically around 1000 cm^{-1}. In the case of MGWP, a broad bandwidth of C_3S absorbance can be seen at 1241 cm^{-1}–932 cm^{-1}. Cement, on the other hand, displays a C_3S absorbance broad bandwidth of 1196 cm^{-1}–1050 cm^{-1}. In terms of the formation of dicalcium silicate (C_2S), it is typically observed around 800 cm^{-1}. In this context, cement demonstrates a bandwidth of 795 cm^{-1}–1050 cm^{-1}, while a 10% replacement shows a belite formation band ranging from 813–668 cm^{-1} [28].
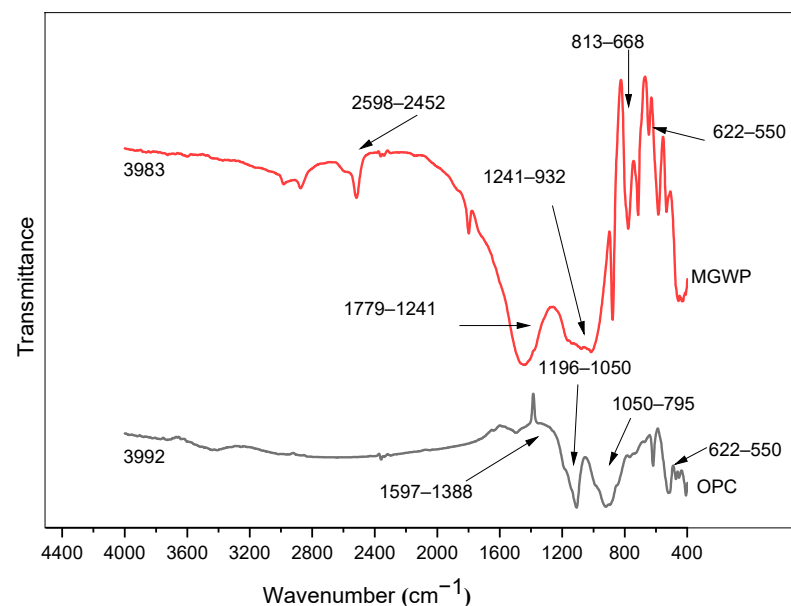
Figure 3. FTIR of the utilized MGWP and OPC.

2.3.2. Thermogravimetric Analysis (TGA)

Thermogravimetric analysis (TGA) techniques were employed to analyze the thermal decomposition of OPC and MGWP (a blend of MWP and GWP in a 1:1 ratio), as illustrated in Figure 4. The initial major decline observed in the TGA curves is associated with the dewatering process occurring within the temperature range of 0 to 120 °C. This process involves with the removal of adsorbed free water or evaporable water present on the surface and porosity of the sample.
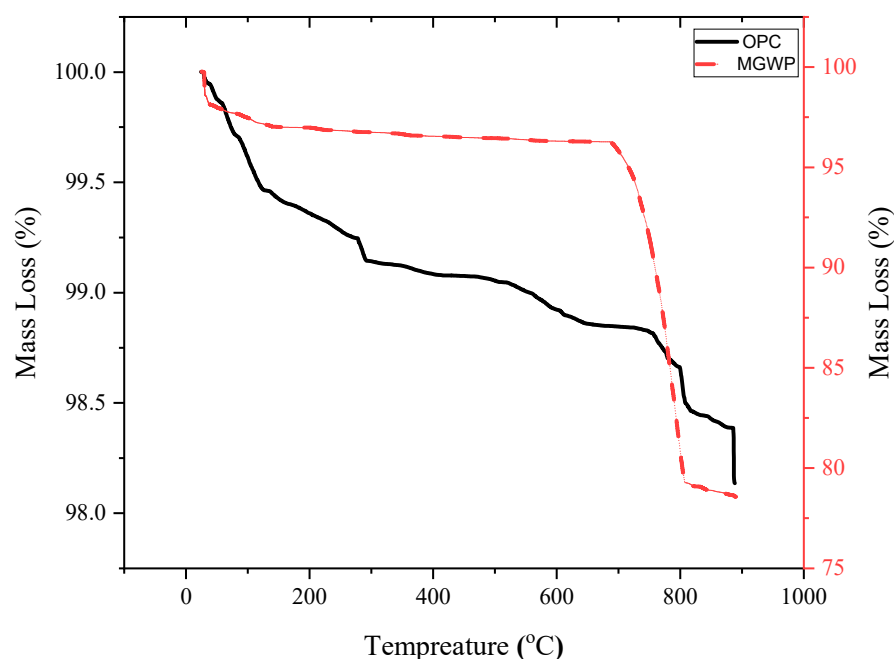
Figure 4. Thermogravimetric analysis of OPC and MGWP.

Figure 4 reveals a significant presence of calcium carbonates in MGWP, and these carbonates exhibit a tendency to decompose when subjected to temperatures within the range of 700 °C to 850 °C. The detection of Portlandite ($Ca(OH)_2$) content was achieved by measuring the loss of hydroxyl ions (OH^-). Likewise, the quantity of calcium carbonate ($Ca(CO)_3$) can be determined by assessing the loss of CO_2 [29]. These findings highlight the thermal behavior and composition of MGWP under varying temperature conditions, providing valuable insights into its potential applications and suitability in different scenarios. As depicted in Figure 4, subjecting MGWP to 100 °C causes a loss of 20% of its mass. In contrast, the reduction in mass observed in OPC is much lower due to the calcination of cement clinker at 1500 °C.

The thermal characteristics of MGWP were studied using differential thermal analysis (DTA), which involved measuring the temperature difference between the MGWP and OPC. The result of the DTA is presented in Figure 5, which provides insights into the thermal behavior of the materials. Phase changes (melting or fusion, vaporization, sublimation, and transition between two structures) occur as a result of endothermic reactions, which also involve dehydration, breakdown, and oxidation. On the other hand, exothermic reactions include freezing or crystallization, phase transitions, decomposition, oxidation–reduction, and chemisorption. The different shapes observed in the DTA results of various materials suggest that the DTA results of MGWP shown in Figure 5 are indicative of calcite.
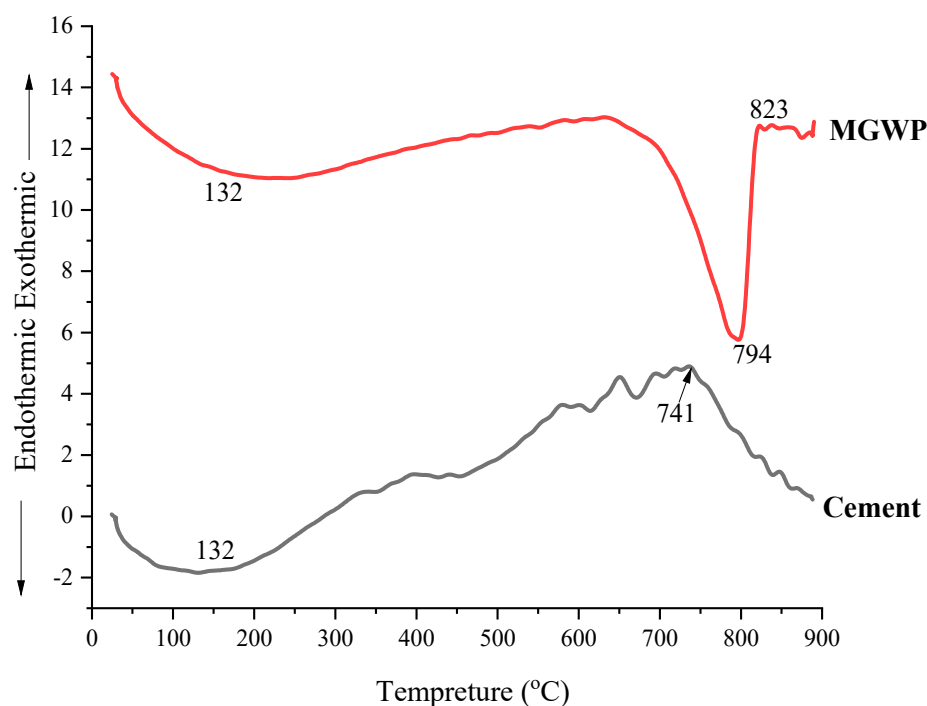
Figure 5. Differential thermal analysis of OPC and MGWP.

2.4. Test Methods for Mortar

Once various tests were carried out to determine the material properties of cement, fine aggregates, and MGWP, the workability, hardened, and microstructural properties of mortar specimens containing both the control and MGWP were evaluated. The testing was performed in accordance with the test methods and categories outlined in Table 4, which comply with the ASTM standards.

The workability of mortar samples was examined using the flow test outlined in ASTM C1437 [30], which is a standardized technique utilized to measure the flowability of mortar. A flow table is used to determine the workability of mortar by measuring the percentage increase in the diameter of the base of a truncated cone when it is placed on the table and mechanically raised 12.7 mm (1/2 in.), and then dropped 25 times in 15 s.

The hardened mortar properties include bulk density, water absorption, compressive strength, homogeneity, and resistance to sulfate attack. To conduct these tests, the mortar mixes were formed into 50 mm × 50 mm × 50 mm cubes. After molding, the cubes were covered with plastic sheets and stored at room temperature for 24 h. They were then removed from the molds and submerged in water for curing until the time of testing. To determine the amount of water absorbed by mortar specimens containing MGWP during a specific period, the water absorption capacity test was conducted. The procedure involved weighing a dry mortar sample, immersing it in water for a set duration, and then reweighing it to determine the amount of water absorbed. This test is essential because it provides valuable information about the porosity and permeability of the mortar specimens, which can significantly affect their overall durability. The water absorption test was performed on each mortar mixture after 3, 7, 28, 56, and 90 days of curing in accordance with the ASTM C642 [31] standard. The compressive strength tests were performed on the samples in accordance with ASTM C109 [32]. The compressive strength test is a critical test that provides the mechanical property of mortar. It is directly related to the structure of the hydrated cement paste, which makes it an important indicator of the overall quality of the mortar. The homogeneity and integrity of the hardened mortar specimens were assessed using ultrasonic pulse velocity tests in accordance with ASTM C597 [33]. This involved using transmission and receiving transducers to send and receive a timed pulse of ultrasonic energy through the mortar cube. The time taken for the signal to pass through

the mortar was then analyzed to determine its homogeneity and integrity. In addition, the resistance of the mortar specimens to sulfate attack was determined by measuring the change in compressive strength.

Thermogravimetric analysis (TGA) and Fourier-transform infrared (FTIR) spectroscopy were utilized to investigate the microstructure properties of MGWP-containing mortar specimens. TGA was performed on selected specimens to evaluate the thermal behavior of the mortar at varying temperatures, determine its chemical composition and stability, and measure its weight loss. On the other hand, FTIR spectroscopy was used to identify and analyze the chemical bonds and functional groups present in the mortar specimens, as well as detect any contaminants or impurities present in the material.

Table 4. The workability, hardened, and microstructural property test results of the mortars.

Test Category	Properties	Test Standards	Examined Samples	Curing Ages
Fresh	Workability	ASTM C1437	All	–
Hardened	Water absorption	ASTM C642 [31]	All	3, 7, 28, 56, 90 days
	Compression strength	ASTM C109 [34]		
	Homogeneity	ASTM C597 [33]		
	Sulfate attack resistance	ASTM C1012/C1012M [35]		
	Bulk density	ASTM C29/C29M [25]		
Microstructure	Thermal decomposition	–	MGWP-0, MGWP-10, MGWP-30	28 days
	Mineralogical composition	–		7 and 28 days

3. Results and Discussion

In this section, we will discuss all of the tests that were performed on mortar containing MGWP. The primary focus of this study is to investigate the impact of partially replacing OPC with MGWP, and therefore all test results are compared with a control mix that only contains OPC as a binding agent. The conducted test examines the characteristics of mortar by assessing the workability of fresh mortar and the physical, mechanical, and microstructural properties of hardened mortar.

3.1. Effects of MGWP on Workability

The workability of the mortar was assessed by measuring its consistency through the flow table method, in accordance with ASTM C1437. Figure 6 displays the test results, which indicate that the flow of the mortar decreases as the proportion of MGWP used to replace OPC increases. According to ASTM C1437, the initial flow of the mortar should be $110 \pm 5\%$. As such, only the fresh mortar mixes containing 5% and 10% MGWP met this requirement, while those with 15% MGWP and higher failed to comply with the standard. This can be attributed to the fact that increasing the proportion of MGWP leads to higher fineness, resulting in increased heat of hydration and water demand for full hydration, which can diminish workability. Furthermore, the higher surface area of the MGWP can absorb more water, further decreasing workability.
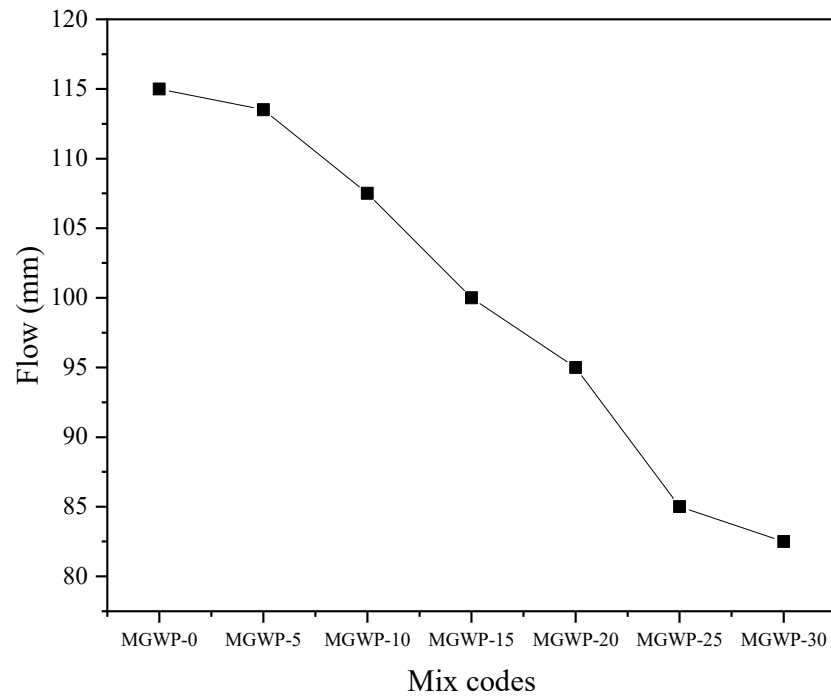
Figure 6. Workability of the mortar mixes.

3.2. Effects of MGWP on Physical and Mechanical Properties of Mortar

3.2.1. Bulk Density

The results of the bulk density tests conducted at 3, 7, 28, 56, and 90 days of curing are presented in Figure 7. It is evident from the figure that the bulk density of both the control and MGWP-containing mortars increases with age, except for the mortar mix containing 5% MGWP. The bulk density of the mortar mix with 10% MGWP replacement is significantly higher than any of the other mixes, followed by the mortar mix containing 15% MGWP. On the other hand, the bulk density of the mortar mixes containing more than 15% MGWP are lower compared to the control mix.
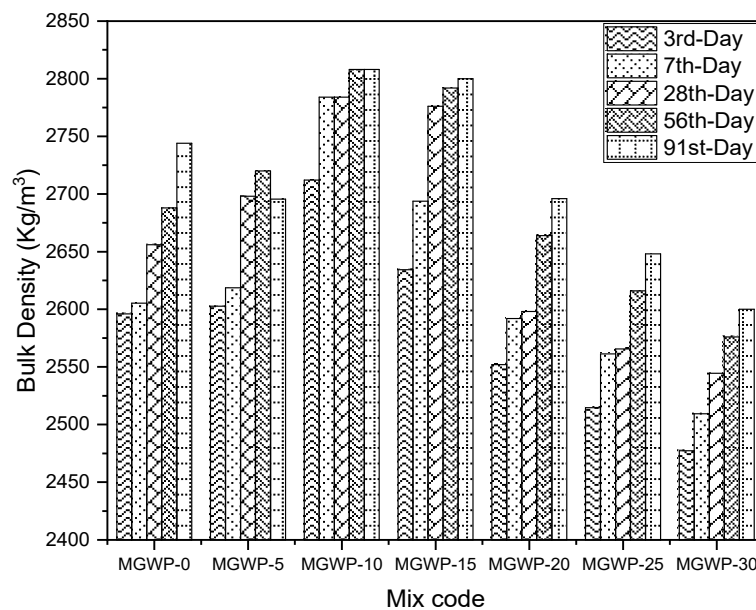
Figure 7. Bulk density of mortar samples with varying percentages of MGWP at different curing ages.

3.2.2. Compressive Strength

The compressive strength of the mortar samples was assessed at various curing ages of 3, 7, 28, 56, and 90 days. The obtained results are displayed in Figure 8. It can be observed that the compressive strength of all the mixes increases with curing age. Notably, the mortar containing 10% MGWP replacement demonstrates the highest compressive strength among all the mixes, while the mortar with 30% replacement exhibits the lowest compressive strength. The enhancement in compressive strength can be ascribed to the elevated CaO content in MWP and SiO_2 content in GWP, resulting in the formation of a more substantial amount of CSH gel. Moreover, the significantly higher specific surface area of MGWP, nearly five times that of cement, promotes increased fineness, fostering a stronger bond between reactants and leading to higher compressive strength. However, further addition of MGWP may lead to a dilution effect in the mix, potentially compromising the overall strength performance.
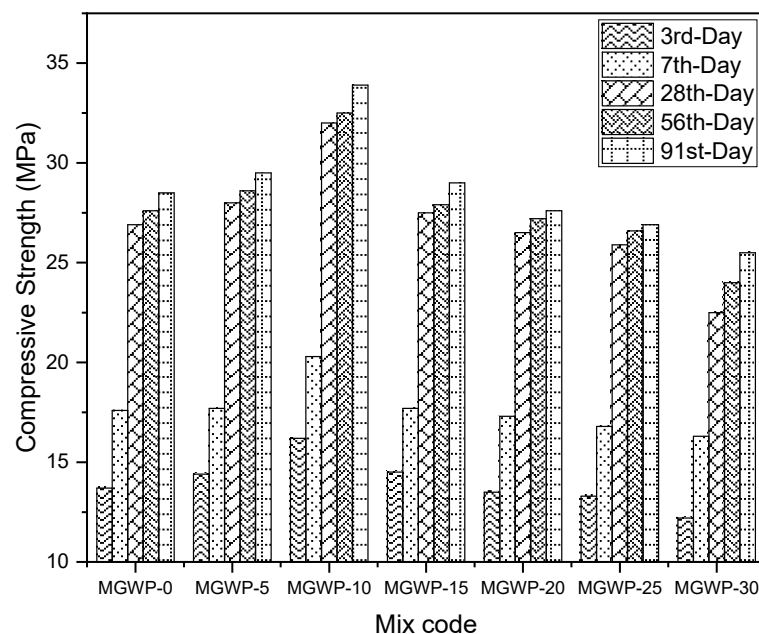

Figure 8. Compressive strength of mortar samples with different percentages of MGWP at various curing ages.

3.2.3. Homogeneity

The homogeneity of the control mortar and mortar containing MGWP was assessed using the ultrasonic pulse velocity (UPV) test, and the results are presented in Figure 9. It can be observed that the UPV values of all MGWP samples increased with the curing age of the mortar. Moreover, an increase in the percent replacement of MGWP up to 15% led to an increase in UPV compared to the control mix, with the highest increment observed for the mortar containing 10% WGWP. This improvement in UPV could be associated with the high content of calcium and silicate minerals, as the quantity of CaO in MWP and SiO_2 in GWP is considerably high. These minerals lead to the formation of a higher degree of CSH gel, which refines the pores of the mortar, eventually improving the UPV. The quality of the mortar in terms of uniformity ranged from medium to good strength according to IS 13311 (Part 1): 1992 [36].

The investigation revealed a positive trend between compressive strength and UPV, where an increase in UPV corresponded with improved compressive strength. The higher UPV values observed for the mortar containing MGWP, particularly at 10% replacement, aligned with the trend of increased compressive strength for the same mix, supporting the notion that improved microstructure and mechanical properties are achieved by incorporating MGWP in the mortar.
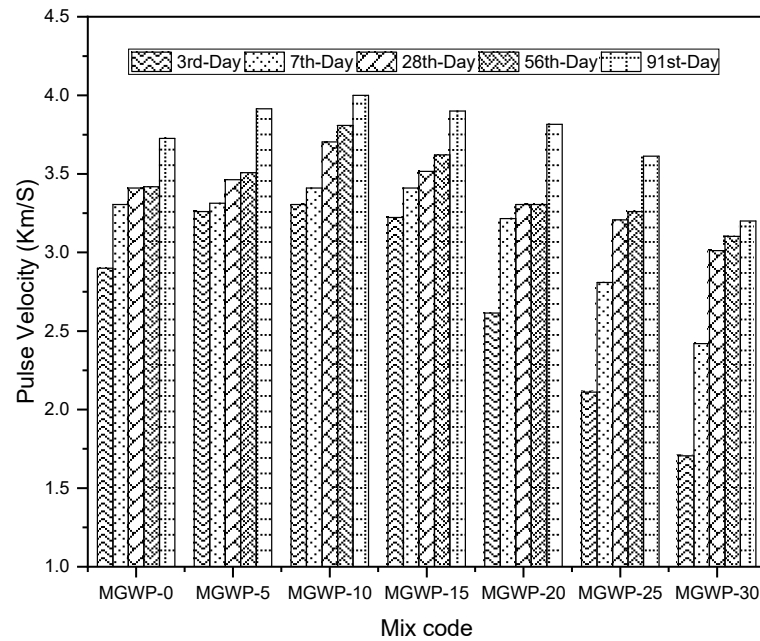
Figure 9. Ultrasonic pulse velocity of mortar samples with varying percentages of MGWP at different curing ages.

3.3. Effects of MGWP on Durability Properties of Mortar

3.3.1. Sulfate Attack Resistance

The compressive strength loss of all mortar samples due to exposure to a sodium sulfate (Na_2SO_4) solution was evaluated to determine their ability to withstand sulfate attack. The results are presented in Figure 10, which shows the loss in compressive strength of the mortar specimens at various curing periods. It is apparent that the compressive strength loss of the mortar containing 10% MGWP is lower than that of the other mixes at all curing ages, indicating its superior ability to resist sulfate attack. This enhancement in resistance could be primarily attributed to the presence of GWP, which is classified as a type N pozzolan and acts as a micro-filler, resulting in higher density and chemical attack resistance [37,38].
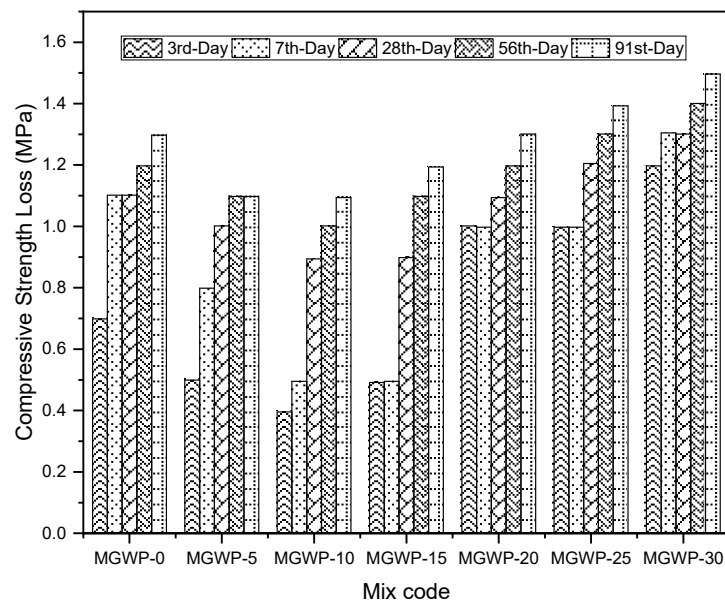

Figure 10. Sulfate attack strength loss in different curing ages.

3.3.2. Water Absorption and Porosity

The water absorption of the control mortar and mortars with varying amounts of MGWP was evaluated using different curing ages, and the results are presented in Figure 11. The test result reveals a decrease in water absorption with increasing curing age and with increasing MGWP content up to 15% when compared to the control mix. Among the MGWP-containing mortars, the sample with 10% WGWP replacement exhibited the lowest water absorption. This result was anticipated due to the more uniform morphology of the mortar.
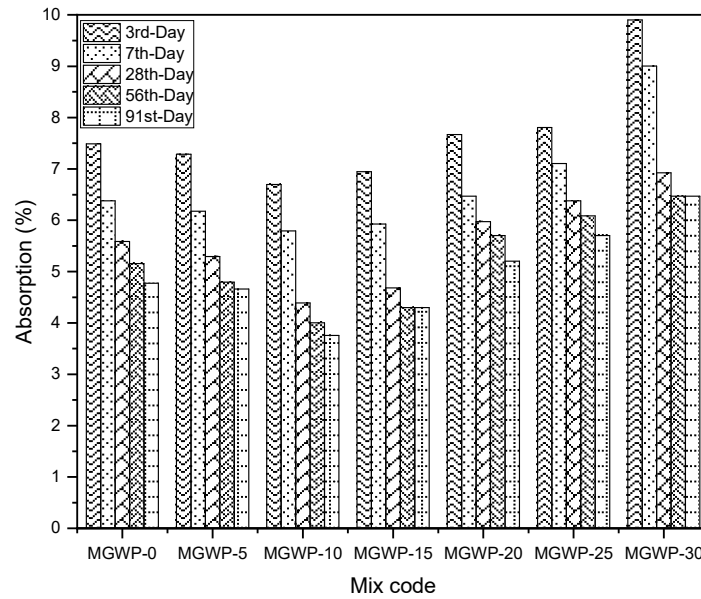
Figure 11. Water absorption of mortar with different percentages of MGWP at various curing ages.

The porosity of all the mortar specimens was also evaluated, and the results are displayed in Figure 12. It can be observed that the porosity of mortar showed a similar pattern to water absorption but was opposite to compressive strength. The replacement of OPC with MGWP up to 15% increased the porosity of mortar, thereby improving its strength and durability.
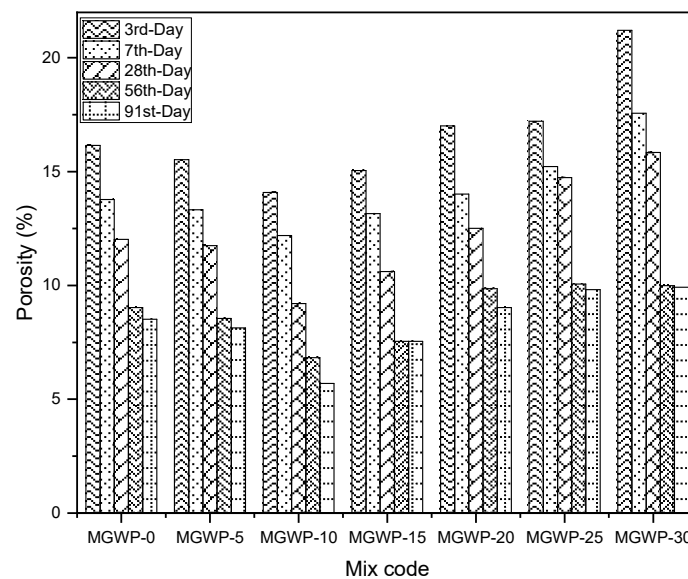

Figure 12. Porosity of the mortar with different percentages of MGWP at various curing ages.

3.4. Effects of MGWP on Microstructure Properties of Mortar

The microstructure of MGWP-containing mortar was analyzed using Scanning Electron Microscopy (SEM), Fourier transform infrared (FTIR), thermogravimetric analysis (TGA), and differential thermal analysis (DTA). The tests were conducted on mortar samples containing 10% and 30% MGWP. The results of these tests were compared to those of the control mix. The findings of each test are outlined below.

3.4.1. Scanning Electron Microscopy

The SEM investigations were carried out on mortar samples cured for 28 days using a JEOL JCM-6000 Plus Bench Top scanning electron microscopy equipment in X 3000 magnification mode. The results of these investigations are depicted in Figure 13. In the control mix (Figure 13a), the C–S–H gel appeared as a foil-like structure. In mortar containing 10% of MGWP (Figure 13b), there is a significant presence of C–S–H gel formation, which fills the voids and pores. Additionally, there is evidence of C–H bonding, which is observed in the form of a plate-like structure. Mortar containing 30% of MGWP (Figure 13c) displayed similar characteristics as the 10% MGWP mix. However, there were additional observations of more voids, which were distinguishable by their dark appearance, and needle-like structures of ettringite in this mix. The presence of a larger void space within the mortar containing 30% MGWP resulted in a reduced contact area between solid particles. Consequently, this led to decreased strength when compared to the mortar containing 10% MGWP, as there were fewer points of contact to resist compressive forces.
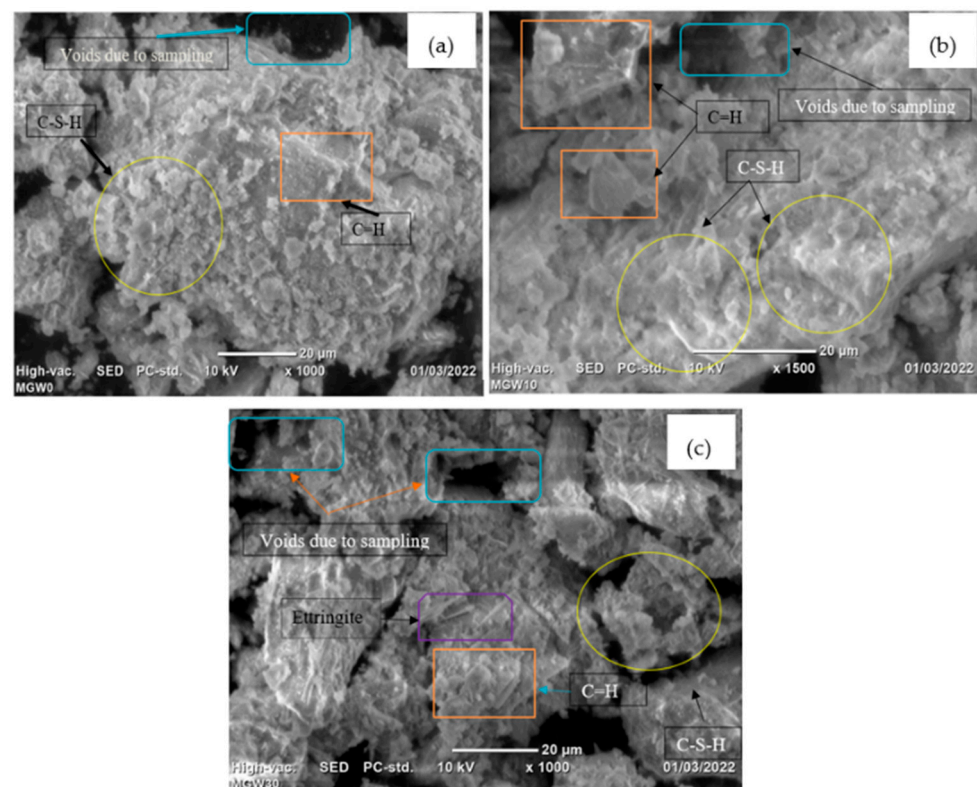

Figure 13. SEM images of (**a**) control, (**b**) MGWP-10, and (**c**) MGWP-30 mixes.

3.4.2. Fourier Transform Infrared

FTIR radiation was passed through mortar samples containing 0%, 10%, and 30% MGWP that were cured for 7 and 28 days. Figure 14 shows the analysis and graphical representation of the infrared radiation absorbance capacity of the materials, with an absorbance band ranging from 4500 cm^{-1} to 400 cm^{-1}.
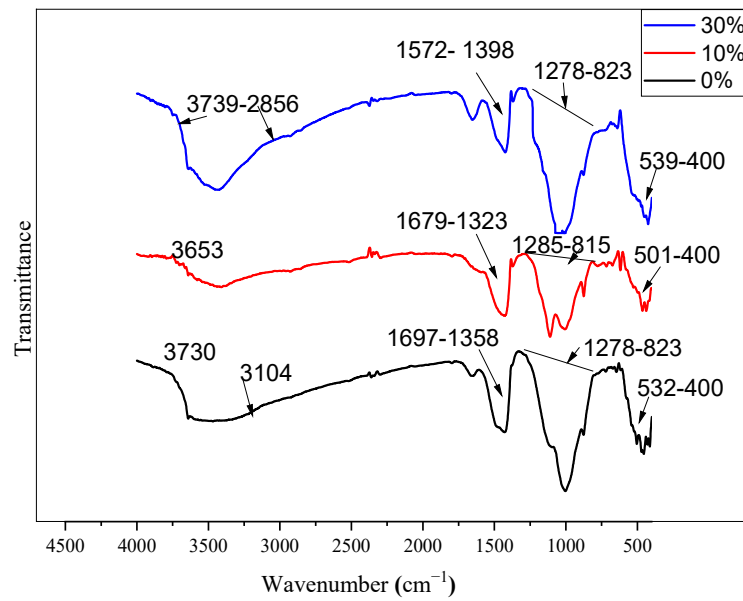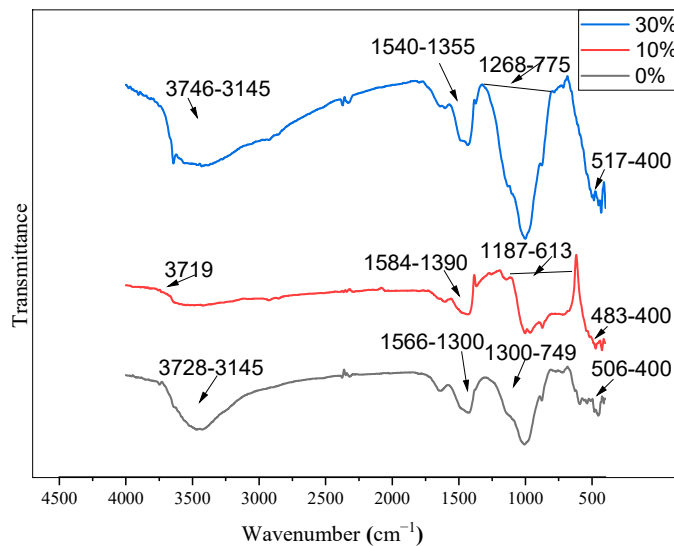
Figure 14. FTIR spectra of mortar samples at two curing ages: (**a**) 7 days, and (**b**) 28 days.

Figure 14a indicates that the FTRI spectra of mortar cured at the age of 7 days and containing 10% MGWP show a broad and deep band at around 1000 cm^{-1} with a shoulder at 1285 cm^{-1}–885 cm^{-1}, which is due to the presence of hydrated silica phases. The hydrated silica phase is also present in the same band in the control mortar sample and mortar containing 30% MGWP, but with a narrower band range of 1278 cm^{-1}–823 cm^{-1} for both samples. Additionally, peaks at 3500 cm^{-1} can be observed, indicating the formation of a strong O–H bond. As depicted in Figure 14b, the same phenomena were observed for the corresponding mortar samples cured for 28 days, albeit with slight differences in peak depth and band ranges.

3.4.3. Thermogravimetric Analysis

Thermogravimetric analysis (TGA) aids in quantification of hydration reactions, as various compositions of cement hydrates can decompose at different temperature ranges during the heating process. This enables the calculation of chemically bound water at a specific age, based on the mass loss of different compounds in pastes, providing an indication of the degree of hydration [39,40].

Figure 15 shows the TGA results obtained from the investigations carried out on mortar samples with 0%, 10%, and 30% of MGWP after being cured for 7 and 28 days. The TGA results presented in Figure 15 indicate that the mass loss of mortar samples containing MGWP is greater than that of the control mix for both 7 and 28 days of curing, with a more pronounced difference observed at a later curing age. Specifically, the difference in mass loss between the control mortar and mortar containing 10% MGWP is 2% at a curing age of 7 days, whereas it is 6% at a curing age of 28 days. The observed mass loss could be attributed to the release of chemically-bound water compounds and the decomposition of calcium carbonate present in MGWP. Although mortar containing 0% MGWP experiences significantly less mass loss compared to mortar with 10% MGWP, its compressive strength is lower. The high mass loss observed in the 10% MGWP mortar can be attributed to the release of chemically-bound water compounds within the MGWP. However, despite this mass loss, the mortar containing 10% MGWP still exhibits higher compressive strength than the mortar without MGWP when both are exposed to high temperatures. This phenomenon can be explained by the pozzolanic reactions occurring between the 10% MGWP and calcium hydroxide, as described in Section 3.4.1. These reactions result in the formation of additional C–S–H gel, leading to a more tightly packed microstructure, which ultimately contributes to the higher compressive strength, even in the presence of potential mass loss.
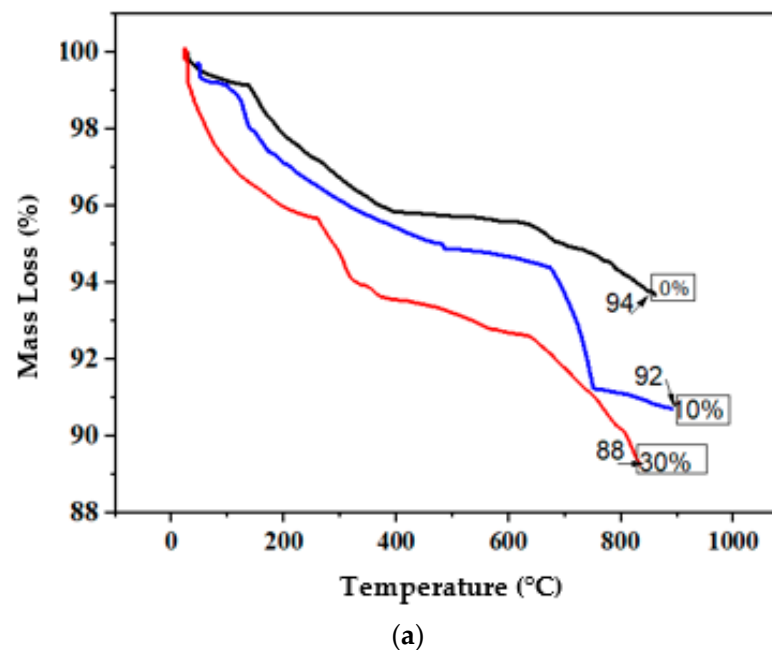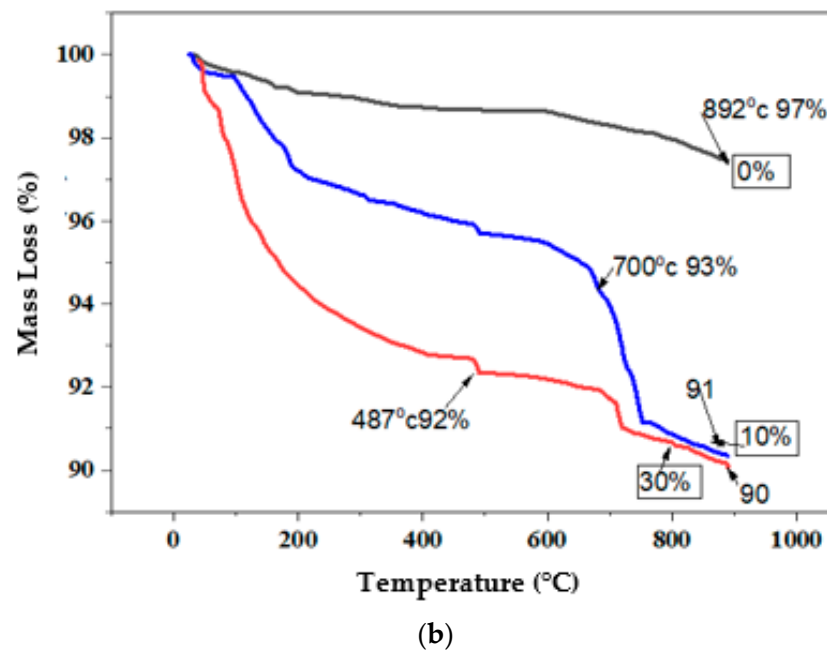

(**a**)

Figure 15. *Cont.*

(b)

Figure 15. TGA curves of mortar samples at two curing ages: (**a**) 7days, and (**b**) 28 days.

3.4.4. Differential Thermal Analysis

Endothermic reactions involve the absorption of heat and can result in phase changes such as melting, fusion, vaporization, sublimation, or transition between two structures. These reactions typically involve processes such as dehydration, decomposition, and oxidation. On the other hand, exothermic reactions release heat and may involve phase changes such as freezing or crystallization, transitions, and reactions such as decomposition, oxidation–reduction, and chemisorption. One application of DTA is to estimate the amount of $Ca(OH)_2$ in cementitious stages by determining the peak regions induced by the breakdown of $Ca(OH)_2$ to $CaO+H_2O$. DTA can also be used as a monitoring tool in the preparation of a nearly $Ca(OH)_2$-free product from hydrated Portland cement or hydrated C_3S [41].

Figure 16a,b show the DTA test outcomes for the mortar samples cured for 7 and 28 days, respectively. The DTA results presented in Figure 16a indicate that the mortar samples cured for 7 days containing 10% of MGWP displayed an early onset of the $Ca(OH)_2$ decomposition peak compared to samples with 0% and 30% replacement. On the other hand, for the mortar samples cured for 7 days with 30% replacement, a small peak at 166 °C was observed due to ettringite decomposition. The DTA curves for all mortars illustrate that the first peak is endothermic, followed by an exothermic peak, and then another endothermic peak. The endothermic peak around 150 °C observed in the DTA curves could be attributed to the breakdown of C–S–H, while the endothermic peak observed around 500 °C could be attributed to the breakdown of calcium hydroxide. The DTA results also show that the calcite present in the mortar samples underwent decomposition at a temperature of 800 °C.
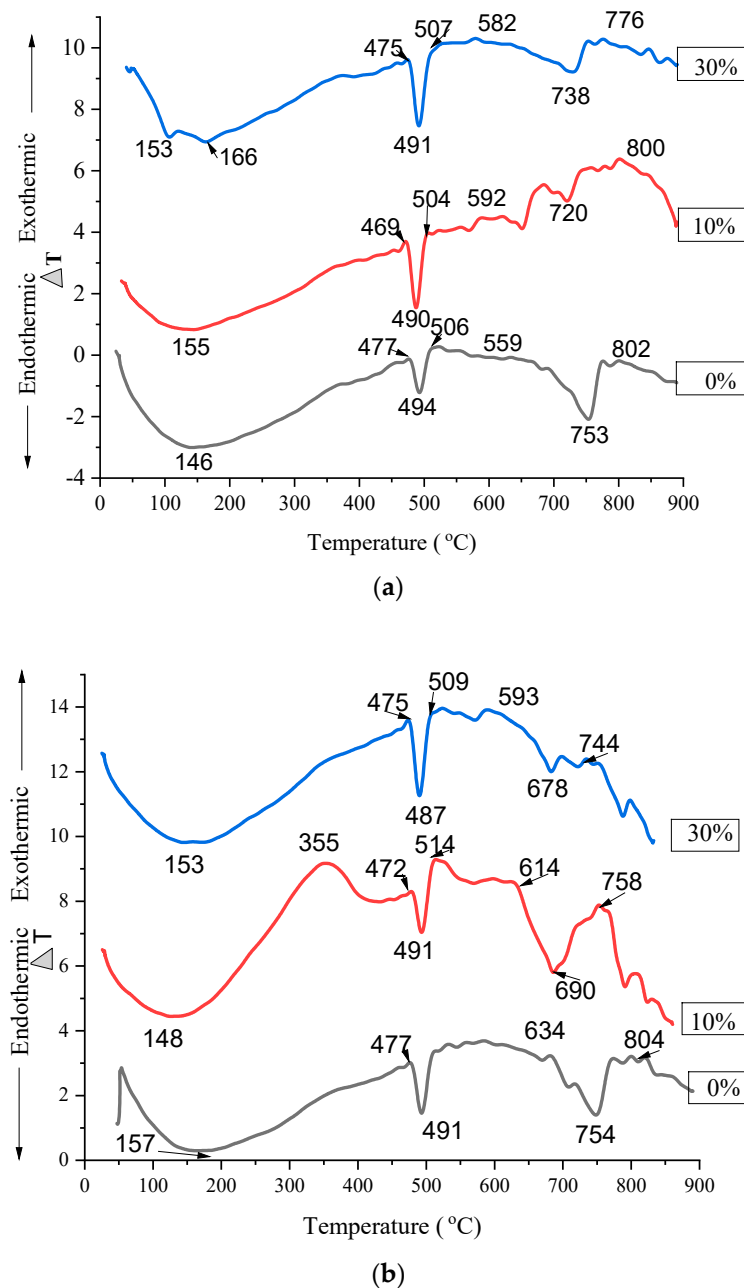
Figure 16. DTA curves of mortar samples at two curing ages: (**a**) 7 days, and (**b**) 28 days.

4. Conclusions

This study focused on investigating the effects of using MGWP, which is a blend of marble waste powder (MWP) and granite waste powder (GWP) in equal ratios, as a partial replacement for OPC at various proportions (5%, 10%, 15%, 20%, 25%, and 30%). The study aimed to evaluate the impact of MGWP on the workability, physical, mechanical, durability, and microstructural properties of mortar. Before conducting the investigation, the MWP and GWP were characterized. From the results obtained, the following conclusions can be drawn:

- As per the ASTM C618 standard, GWP can be categorized as a Class N natural pozzolan material, which signifies its pozzolanic properties. However, MWP does not meet the requirements to be classified as a pozzolan material according to the same ASTM standard.

- As the percentage of MGWP increased, the workability of the mortar mixes decreased, which can be attributed to the higher fineness of the MGWP particles.
- The addition of up to 15% MGWP led to an improvement in the bulk density, compressive strength, and homogeneity of the mortar, with the mortar containing 10% MGWP showing the best performance in these tests. Similar improvements were also observed in properties related to durability, specifically resistance to sulfate attack, water absorption, and porosity.
- A microstructure analysis confirmed that the addition of MGWP resulted in changes in the structure of C–S–H gels in the mortar samples. The morphological structure of the mixes became denser up to a 10% content of MGWP. However, a slight increase in mass loss was observed with an increase in MGWP content when exposed to high temperatures.
- Replacing up to 10% of cement with MGWP in mortar can improve its physical, mechanical, and durability properties. Incorporating the MGWP, which would otherwise be landfilled, in the mortar allows for a reduction in the usage of OPC. This reduction could contribute to achieving sustainability in the concrete industry.

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