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The effect of siliceous types as pozzolanic materials and aggregate types on the properties of cement mortar

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ABSTRACT

Portland cement can be considered as the most important building materials, but cement production is associated with high carbon dioxide emissions. different materials were added to cement mortar and concrete to improve their properties and reduce the amount of cement in their mixtures. In this research, to produce sustainable cement mortar, the effect of adding various siliceous materials [Silica (SiO_2) is the main constituent] as pozzolanic materials on the properties of cement mortar with and without waste fine aggregate was investigated. Silica fume, silica powder, and waste glass powder were used to replace (2.5, 5, and 10) weight percentages of cement in the cement mortar mixture with natural sand. While 5% silica fume, 10% silica powder, and 5% waste glass powder were used to replace cement in cement, a 25-weight percentage of waste mortar was used as a fine aggregate to replace virgin aggregate in mortar mixtures. The flexural and compressive limits were evaluated for all cement mortar samples, while scanning electron microscopy (SEM) was characterized for some samples (control and high compressive strength). The findings indicate that the siliceous materials used in this study enhanced the compressive strength of cement mortar by altering its microstructure. The maximum compressive strength of 36.16 MPa was achieved in samples that contained 5% silica fume in a standard cement mortar, while samples that contained 100% waste fine aggregate and 2.5% waste glass had a lower compressive strength (17.89 MPa) than all samples of cement mortar prepared by this research for 28 curing days.

Keywords: *Waste aggregate, Waste glass, Silica fume, SEM*

1. INTRODUCTION

Structures and construction materials are important subjects in sustainable development due to their environmental effect. Concrete is the biggest and most important building material, which needs large raw materials in its mixture (cement, fine and coarse aggregates, and additives), which leads to a huge impact on the environment for two reasons. The first is the use of a large number of natural resources, and the second is the emission of carbon dioxide. For example, producing a single ton of Portland cement requires a total of 1.5 tons of initial components, resulting in about one ton of CO_2 emissions [1–3]. A Pozzolanic material is a siliceous and aluminous substance that has little or negligible cementitious properties on its own. Nonetheless, It may chemically react with calcium hydroxide ($Ca(OH)_2$) at ambient temperatures and in the presence of moisture to produce compounds with cementitious characteristics or to expedite this process [4, 5] . There are numerous by-products and wastes from multiple manufacturing and production processes that can be used to provide a source of silicon oxide, aluminium oxide, calcium oxide, and iron oxide as pozzolan materials in cement mixtures. Cement kiln dust (CKD) is a cement manufacturer's waste product. Silica vapor is an outcome of silicon metal or ferrosilicon alloy production. Fly ash and bottom ash from electric power plants and three waste materials from the iron industry can be used in the making of sustainable cement, such as foundry sand, mill scale, and slag [6–10].

Sustainable cement materials can be produced by various methods, such as using waste materials to replace natural aggregate, or as a pozzolanic substances that enhance the resilience of cement mortar and concrete (the first building material used in the world) [11–14]. Silica fume (SF) was used in many research studies to improve concrete properties because of its cementitious behavior or ability to fill the holes between concrete mixtures [15, 16]. Silica powder (SP) is considered chemically inert at normal ambient temperatures, but its addition to the Portland cement mixture accelerated the hydration reaction of the cement because of its physical properties [17, 18].

Glass is one of the most widely used materials for various purposes, and glass is considered a non-biodegradable material. So that glass waste spread widely in world. Therefore, the trend has been to recycle it and use it for different purposes. One of those uses is its use as pozzolanic materials added to a cement to improve its properties and production sustainable concrete [19–23]. So that research uses different siliceous materials (silica fume (SF), silica powder (SP), and waste glass powder (GP)) at various percentages to provide silica and waste fine aggregate (W) from concrete demolition in cement mortar mixtures to produce sustainable concrete, then investigates their influences on the compressive strength of normal cement mortar and cement mortar with waste fine aggregate.

2. MATERIALS AND METHODS

2.1. Cement

Karasta CEM II/A-L 42.5 R (moderate sulphate-resistant or moderate heat cement) cement type is used for general purposes by Lafarge Iraq Company and is used in this research. Cement properties are shown in Table 1.

2.2. Natural Sand

Natural sand (fine aggregate) with a red colour from the Karbala region was used to manufacture cement mortar. Sand sieving analysis was done as shown in Table 2.

2.3. Siliceous Materials

Three types of silica supplemental materials are used in this research: pure white silica powder (99%) 74 micron from Riedel-De Hean Hannover (Honeywell)/Germany; silica fume (92%), from Henan Superior Abrasives Co., Ltd./China; and glass powder have grain size between 150 to 75 microns, its product by recycling broken colourless soda lime glass.

2.4. Waste Aggregate

The concrete waste from demolition was recycled into fine particles after broking; milling and sieving for the required size shown in Table 3 were employed to substitute a portion of the fine natural aggregate in cement mortar simples. The compared-grained distribution between natural and waste aggregate is shown in Figure 1. The aggregate bulk density for natural sand and prepared waste aggregate was assessed in accordance with ASTM C 29 [24], as seen in Table 4.

2.5. Preparation of Mortar Samples

In addition to the control sample (a sample of cement mortar without any addition), seven groups of cement mortar were prepared in this research, as shown in Table 5. Three groups of cement mortar were prepared by the addition of 2.5, 5, and 10 weight percentages of silica fume, silica powder, and waste glass to replace part of the cement mortar with natural sand. The fourth group, for cement mortar, was prepared using waste cement mortar as fine aggregate to replace natural sand by 25, 50, and 100 weight percentages. Finally, three groups of samples were prepared with the addition of silica fume, silica powder, and waste glass percentages that have the highest compressive strengths in the first three groups to replace cement and the waste cement mortar aggregate to replace natural sand. The control specimen and the waste cement mortar were both made using a cement-to-sand ratio of 1:3 and a water-to-cement ratio of 0.50. While a water/blend ratio of 0.5 was used for all remaining samples, the samples were cured in water for 7 and 28 days, respectively.

Table 1. Portland cement chemical analysis

Oxide	Weight %	Limits of Iraqi specification No. 5/1984
Al_2O_3	5.31	-
CaO	63.17	-
SiO_2	18.45	-
SO_3	2.29	< 2.8
MgO	2.32	<5.00
Fe_2O_3	3.37	-
Loss on ignition	3.75	< 4.00
Insoluble residue	1.34	< 1.50
Lime saturation factor	0.98	0.66-1.02
Specific surface area m^2/kg	370	-

Table 2. Sand grading and requirements

Sieve size (mm)	Accumulative Passing %	Accumulative Passing %
4.75	100	90–100
2.36	92.51	85–100
1.18	87.22	75–100
0.60	67.85	60–79
0.30	28.53	12–40
0.15	8.91	0–10

Table 3. Waste fine aggregate sieving

Sieve size (mm)	Accumulative Passing %
4.75	100
2.46	100
1.18	84.61
0.60	78.85
0.30	35.73
0.15	6.14

Table 4. Natural sand and waste fine aggregate density

Aggregate type	Loose bulk density (kg/m³)	Compact bulk density (kg/m³)
Natural sand	1.497	1.583
Waste fine aggregate	1.434	1.515

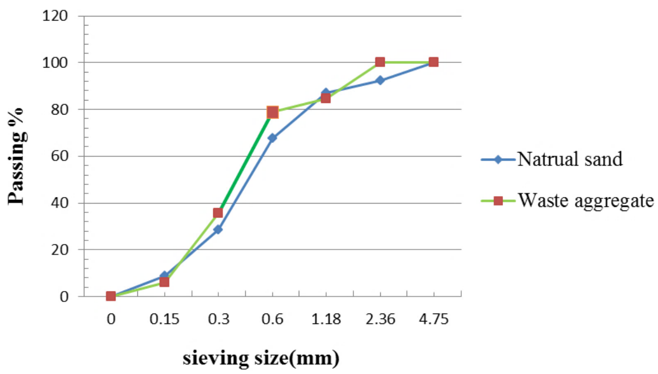

Figure 1. Comparing the grained distribution between natural sand and waste aggregate

Table 5. Mix proportions of cement mortar samples

No.	Group no.	Mortar mix.	Cement (g)	Sand (g)	Silica fume (g)	Silica powder (g)	Waste glass (g)	Waste fine aggregate (g)
1	Control	Co	70.00	210.0	0.00	0.00	0.00	0.0
2	G1	2.5 SF	68.25	210.0	1.75	0.00	0.00	0.0
3		5 SF	66.50	210.0	3.50	0.00	0.00	0.0
4		10 SF	63.00	210.0	7.00	0.00	0.00	0.0
5	G2	2.5 SP	68.25	210.0	0.00	1.75	0.00	0.0
6		5 SP	66.50	210.0	0.00	3.50	0.00	0.0
7		10 SP	63.00	210.0	0.00	7.00	0.00	0.0
8	G3	2.5 GP	68.25	210.0	0.00	0.00	1.75	0.0
9		5 GP	66.50	210.0	0.00	0.00	3.50	0.0
10		10 GP	63.00	210.0	0.00	0.00	7.00	0.0
11	G4	25 R	70.00	157.5	0.00	0.00	0.00	52.5
12		50 R	70.00	105.0	0.00	0.00	0.00	105.0
13		100 R	70.00	0.0	0.00	0.00	0.00	210.0
14	G5	5 SF 25 R	66.50	157.5	3.50	0.00	0.00	52.5
15	G6	10 SP 25 R	63.00	157.5	0.00	7.00	0.00	52.5
16	G7	2.5 GP 25 R	68.25	157.5	0.00	0.00	1.75	52.5

2.6. Compressive Strength Test

The compression test was done for all prepared samples in the engineering college at Mustansiriya University; according to ASTM C 109 [25], a cubic mold with a dimension of 2 inch (50 mm) was used to produce specimens.

2.7. Flexural Strength

The third point load is used to test the flexural strength (modulus of rupture) for 7- and 28-day curing, which is a measure of the tensile strength in bending because in this test the sample is subjected to bending only and the shear effect is zero. Prismatic specimens with dimensions (40 × 40 × 160) mm were prepared according to ASTM C348-21 [26] with a loading ratio of 1kN/S.

2.8. Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) was employed to examine the morphology of many produced cement mortar samples (the control sample and the samples have high compressive strengths). The samples were cured for 28 days. A scanning electron microscope (SEM) (Type TESCAN) at the Technological University of Baghdad was used in this work.

3. RESULTS AND DISCUSSION

3.1. Compressive Strength for Natural Fine Aggregate Cement Mortar with Silica Pozzolanic Materials

The compressive strength of cement mortar was affected by the addition of different types of silica-containing materials compared to cement mortar without additives (the control sample). The incorporation of silica fume enhanced the compressive strength of the cement mixture in comparison to the control sample over various curing durations (7 and 28 days), as seen in Figures 2 and 3. That may be due to the nature of amorphous silica dust, which is highly active because of the large specific area of its granules, which led to improved bonding and accelerates the hydration process of cement mortar mixtures, as illustrated in Figure 4(B). The highest compression strength was attained by including 5% silica fume into the cement mortar, yielding 23.08 MPa and 36.13 MPa at 7 and 28 curing days, respectively. Increasing the silica fume percentage above 5% results in a reduction in compressive strength, while it remains superior to that of the control specimen. Compared to the control sample, it is still better. This phenomenon may be attributed to the agglomeration of silica fume or inadequate hydration of the cement mixture owing to insufficient water content. Silica powder enhances the compressive strength of cement mortar. Nonetheless, the compressive strength escalates with the proportion of included silica powder. The maximum compressive strengths were achieved by including 10% silica powder into the cement mortar mixture, yielding 22.14 MPa and 33.62 MPa at 7 and 28 curing days, respectively. This may result from the pozzolanic characteristics of silica powder and its enhanced distribution, which produce solute silicic acid from active silica that reaction water and CaO or soluble calcium hydroxides at room temperature lead to formation hydraulic products. Which altered the cement paste structure by augmenting the robust calcium silicate gel (C–S–H) and reducing the generation of soluble calcium hydroxides ($Ca(OH)_2$) in the cement mortar mixture to produce strong dense matrix [27–29], as illustrated in Figure 4(C). The incorporation of waste glass powder stemmed from the crushing and grinding of colorless glass to partially substitute cement in the cement mortar composition. The compressive strength rose with the addition of glass powder up to 5% (20.72 and 26.12 MPa for 7 and 28 curing days, respectively) in comparison to the control sample. The interaction between silica in the glass composition and alkali in the hole of cement paste lead to dissolving the silica, as a result of the increase in the pozzolanic activity of the glass powder when its particle size becomes smaller because its surface area increases. That helps to produce a C–S–H gel due to pozzolanic reaction of silica and calcium hydroxide, which enhances the strength

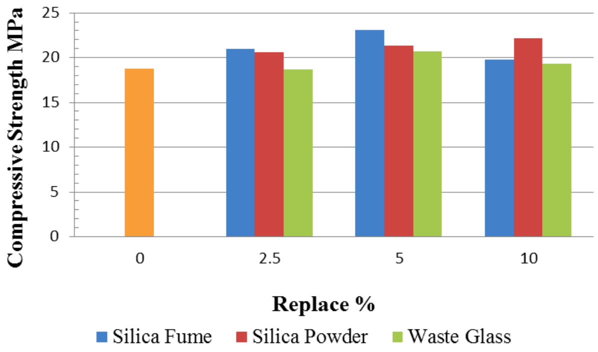

Figure 2. Compressive strength for 7 days curing samples

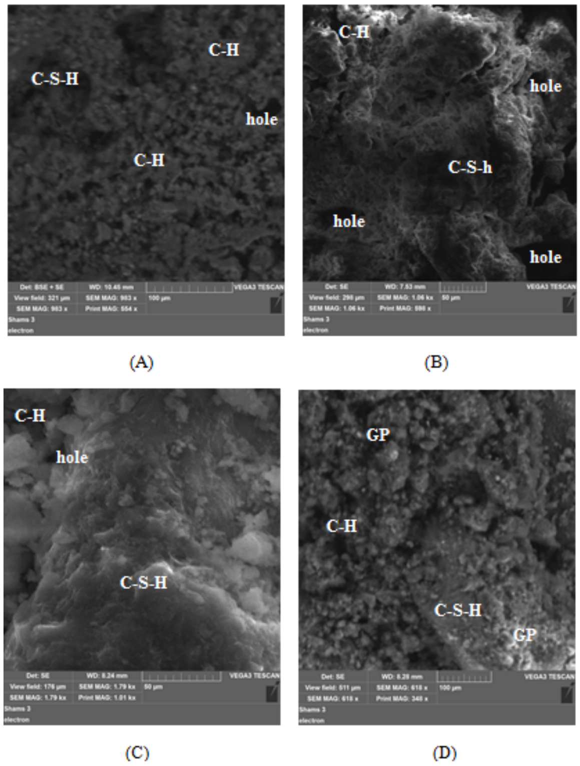

Figure 4. SEM cement mortar samples (A) Control sample, (B) 5% silica fume, (C) 10% silica powder, and (D) 5% waste glass powder

of the cement mortar [30–32]. Moreover, glass powder occupies the voids in the cement composite. Increasing the glass powder percentage above 5% (25.23 MPa) resulted in a reduction in compressive strength, however it remained superior to the compressive strength of the control sample, as seen in Figures 2 and 3.

Strength activity index (SAI) according to ASTM C 311 [33] is:

$$SAI = (6A/6B) \times 100 \quad (1)$$

where, 6A denotes the average compressive strength of blended cement mortar, and 6B represents the average compressive strength of the control sample mortar.

Strength activity index was calculated for samples 28 day curing as shown in Figure 5.

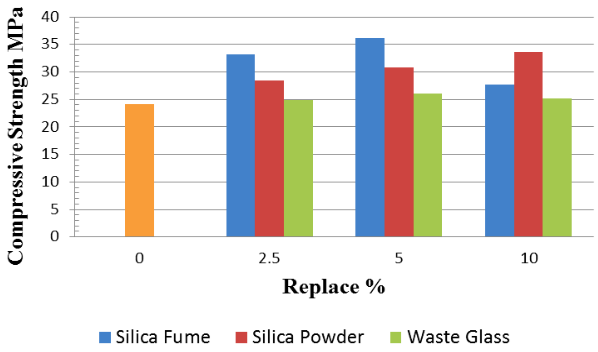

Figure 3. Compressive strength for 28 days curing samples

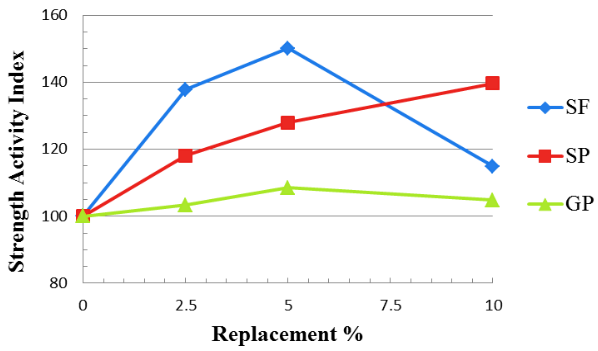

Figure 5. Strength activity index for 28 day curing samples

3.2. Flexural Strength for Natural Fine Aggregate Cement

Mortar with silica pozzolanic materials substituting 5% of cement with silica fume resulted in the maximum bending strength (3.83 and 6.02 MPa for seven and twenty-eight days of curing, correspondingly) when compared to other produced cement mortar samples. While, lowest flexural strength was obtained in replace cement with 10% of glass powder as shown in Figures 6 and 7. The reason for this is that the silica in the silica fume reacts with the $Ca(OH)_2$ that is generated during the cement mortar's hydration process to produce more calcium silicate hydrate (C–S–H), which increases the cement mortar's strength and requires just enough water to finish the hydration process. While the increase in glass powder causes more an alkali-silica reaction (ASR) that led to decrease cement mortar properties.

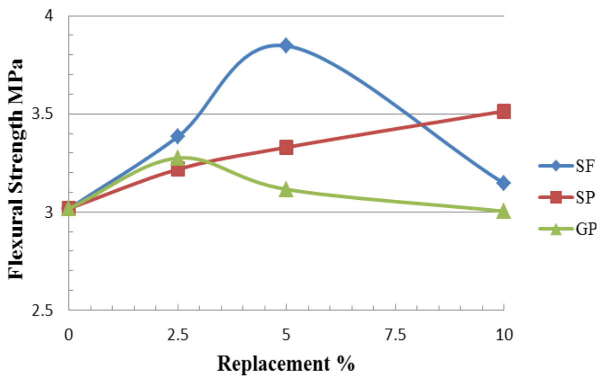

Figure 6. Flexural strength for 7 days curing samples

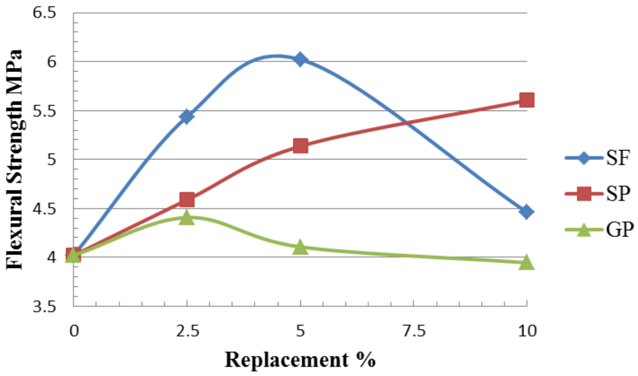

Figure 7. Flexural strength for 28 days curing samples

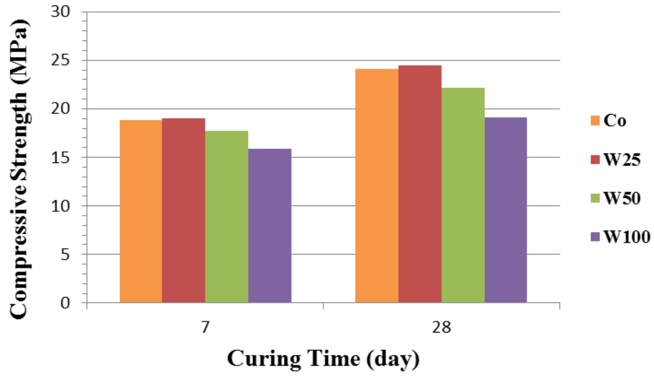

Figure 8. Compressive strength for waste cement mortar

3.3. Compressive Strength for Waste Fine Aggregate Cement Mortar

Fine aggregate is derived from crushed concrete for use in cement mortar to create sustainable concrete. Various proportions of 25%, 50%, and 100% waste aggregates were included to substitute the natural aggregates in the cement mortar formulation. As shown in Figure 8, the cement mortar's compressive strength increased somewhat when 25% of the fine aggregate was substituted; it was 19.03 MPa at 7 days and 24.45 MPa at 28 days. The slight increase may be ascribed to the higher ratio of cement in the mixture, due to the inclusion of non-reactive cement that produces C–S–H gel with ($Ca(OH)_2$), as seen in Figure 12 (A). Cement mortar's compressive strength decreases when natural fine aggregate is substituted more often, as seen in Figure 5. This results from the heightened demand for waste aggregate in water, which causes an increase in porosity and a deterioration of cement mortar owing to incomplete hydration of the cement mortar mixture. The decreased compressive strength results from an increase in waste aggregate exceeding 25% in the cement mortar mixture relative to a control sample.

3.4. Compressive Strength for Waste Fine Aggregate with Siliceous Pozzolanic Materials Cement Mortar

Twenty-five percent of the natural sand was substituted with waste fine aggregate in cement mortar mixes, and 5% silica fume, 10% silica powder, and 5% waste glass powder, respectively use to replace cement in cement mortar mixes, to investigate the impact of this substitution on compressive strength, flexural strength, and cement hydration. The combination of 5% silica fume, 10% silica powder, and 5% glass powder exhibits the greatest strength activity index, as seen in Figure 5, and was therefore selected. The maximum compressive strength attained was 35.02 MPa by replacing 25% of the genuine sand with waste fine aggregate in the cement mortar mixture containing 5% silica fume, as demonstrated in Figure 9. A minimum compressive strength of 17.98 MPa was attained by replacing 25% of the natural fine aggregate with waste fine aggregate in the cement mortar mixture containing 5% waste glass powder, as seen in Figure 11. Despite the reduction in compressive strength across all samples upon substituting natural aggregates with waste aggregates, there is an observed enhancement in the hydrogenation

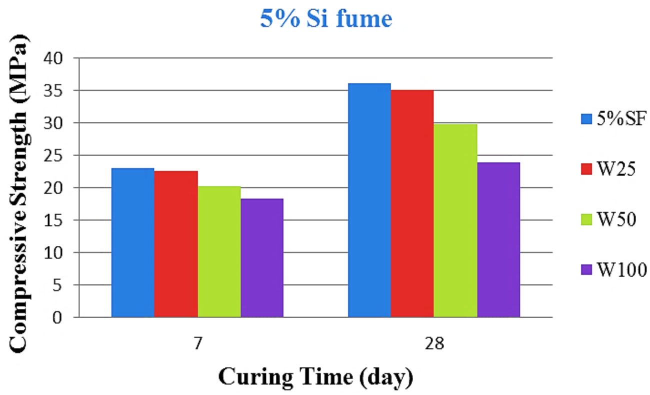

Figure 9. Compressive strength for 5% silica fume and 25% waste aggregate cement mortar

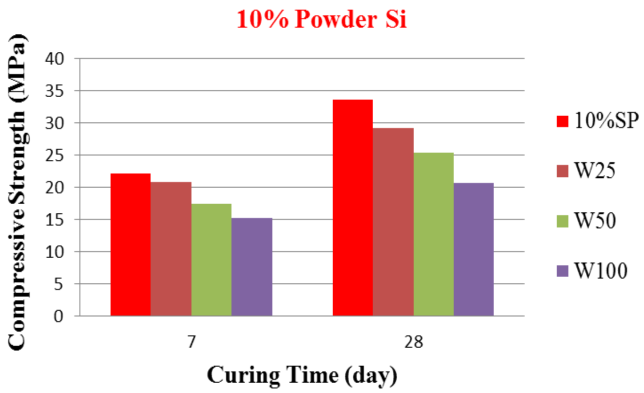

Figure 10. Compressive strength for 10% silica powder and 25% waste aggregate cement mortar

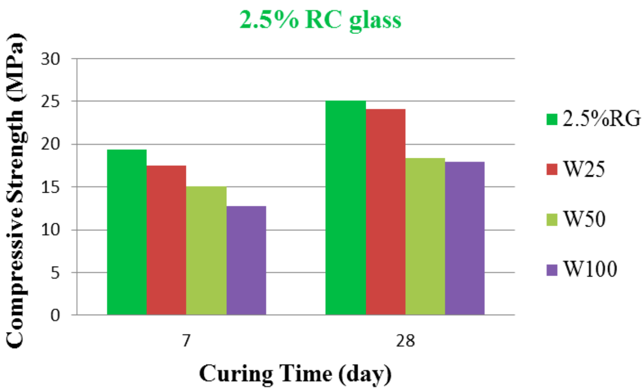

Figure 11. Compressive strength for 5% waste glass and 25% waste aggregate cement mortar

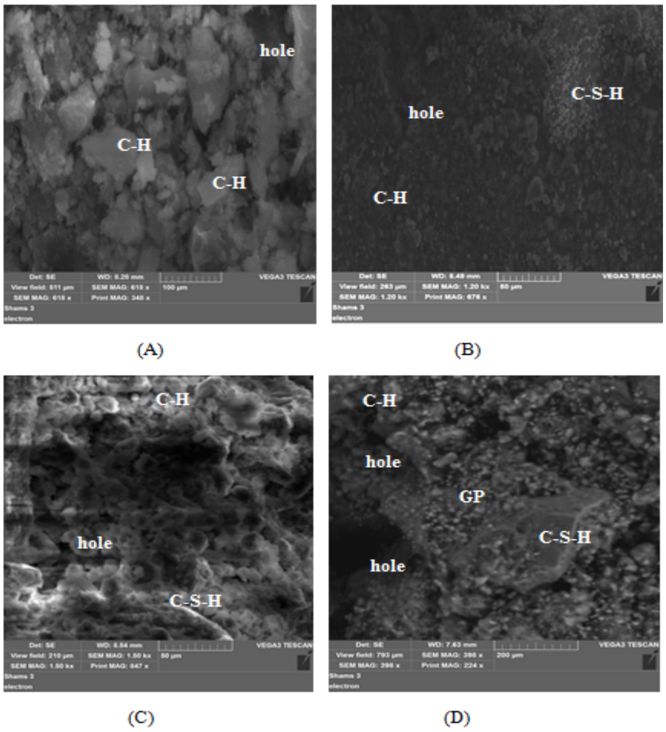

Figure 12. SEM cement mortar with waste fine aggregate samples(A) 25% waste fine aggregate only, (B) with 5% silica fume, (C) with 10% silica powder, and (D) with 5% waste glass powder

process of the cement mortar mixture, shown by the increased creation of C–S–H gels, as seen in Figure 12 (B, C, and D). This elucidates the superior compressive strength of the majority of combinations in comparison to the sample mixture (R25).

4. CONCLUSION

Substituting varying percentages of cement with siliceous materials (silica fume, silica powder, and waste glass powder) at distinct weight ratios in the cement mortar mixture significantly influenced the compressive strength and microstructure as shown below:

Augmenting the amounts of cement replacement to 5% silica fume enhanced the mechanical qualities of cement mortar. The compressive strength increased by 22.7% and 50.1%, and the flexural strength increased by 27.4% and 49.7% for 7 and 28 curing days, respectively, when compared to the original mortar sample containing natural sand; additionally, there was an enhancement in the formation of C–S–H gel and a reduction of gaps in the microstructure.

The use of silica powder led to an enhancement in compressive strength with a substitution ratio increase of up to 10%. The percentage increase in compressive strength (17.7% and 39.7%) and flexural strength (16.4% and 39.3%) for seven and twenty-eight days of curing, accordingly, in relation to the compressible strength of the control specimen. The microstructure exhibits a significant proportion of $Ca(OH)_2$ relative to the cement mortar containing 5% silica fume.

The optimal replacement ratio for waste glass powder was 5%, although it did not result in a notable enhancement in compressive strength. The increase ratios of compressive strength were 10.1% and 8.5% for 7 and 28 curing days, respectively, in comparison to the control sample. The enhancement in flexural strength was 6.5% and 17.4% for curing periods of 7 and 28 days, respectively, in comparison to the control sample. This may explain the efficacy of the pozzolanic properties in this material; yet it is deemed sustainable due to its reduction of glass waste in landfills.

Optimal results were achieved by substituting natural aggregate (sand) with waste fine aggregate at a rate of 25%, resulting in a compressive strength enhancement of 1.2% and 1.6% for 7 and 28 curing days, respectively, in comparison to the control sample's compressive strength. This is a consequence of increasing the quantity of cement in the mixture. Nonetheless, augmenting the replacement ratio concluded in a decrease in compressive strength. The particle size and the aggregate debris may need more water to complete the hydration process. The incorporation of silicate materials (5% silica fume, 10% silica powder, and 5% waste glass powder) with 25% waste aggregates led to a decrease in the compressive strength of the cement mortar, as opposed to the peak compressive strength attained for each separate silicate ingredient. Nevertheless, the compressive strength was enhanced relative to the control sample (a mortar sample devoid of replacement).

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