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Properties of blended mortars produced with recycled by-products from different waste streams

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ABSTRACT

The construction industry encounters significant challenges in effectively managing solid waste produced during the extraction and production of building materials. In different countries, slurry waste generated from granite and marble processing industries, such as glass industry waste, constitutes a considerable portion of the total solid waste. Its undesirable disposal is causing unprecedented environmental damage. Using these non-biodegradable wastes to produce building materials would reduce the environmental burden and contribute to sustainable construction. This study, in detail, investigates the feasibility of utilizing Granite Powder (GP), Ground Granite Powder (GGP), and Ground Glass Waste (GGW) as partial replacements of components in blended mortar mixes. The mix modifications consist of partial replacement of cement with GGW, GP, and GGP in the range of 5–15% and fine aggregate replacement with Marble powder (MP) in 10–30% by mass. The mechanical, physical, and microstructure properties of blended and control mortar mixes were studied on the 3rd, 7th, 28th, and 91st curing days. The results demonstrate that the partial substitution of 10% GGW and 5% GP with cement and 10% MP with fine aggregates in blended mortars enhance the compressive strength at the later curing age (28 and 91 days) compared to that of a control mortar, which is associated to the development of higher pozzolanic reactivity. The XRD results showed the formation of the lowest content of calcium hydroxide (CH) and the highest content of calcium silicate gel in the blended mortars compared to the control mortar. The results enrich the data available in the literature not always univocal, as in the case of using marble and glass waste, providing also interesting information about the influence of granite powder on the hydration process in a mortar mix actually missing.

1. Introduction

Concrete and mortar have been leading construction materials for over a century reaching actually an annual global production of several billion m^3 (Jain et al., 2020a). The impact on the environment is not negligible both for the production of aggregates, which are a non-renewable resource (Coffetti et al., 2022), and cement, which contributes to a high amount of the total anthropogenic greenhouse gasses (Hossain et al., 2021; Damineli et al., 2010; Scrivener et al., 2008; Mehta and Ashish, 2020). The impact of concrete production could be reduced by the reuse of industrial by-products for the substitution of both aggregates and cement. In detail, granite, marble, and glass wastes are considered here because of their abundance in different countries, which causes detrimental environmental and health problems (Ghani et al., 2020; Noreen et al., 2019). Different studies have been conducted on the feasibility of waste for construction materials (Rodrigues et al., 2015; Ferrotto et al., 2022). However, non-univocal results can be found in the literature as regards of their effectiveness. Further approaches and experimental campaigns are desirable. For example, marble waste as a sand substitute (Ashish, 2019; Ashish et al., 2016), as a substitute of cement and sand amalgam in producing concrete (Ashish, 2018), and in producing cement mortar (Gupta and Vyas, 2018; Kabeer and Vyas, 2018) was investigated and discussed without stating definitively the role of marble in the hydration process. Kabeer and Vyas (2018) substituted river sand with marble waste from 0 to 100% at 20% intervals in cement mortar and achieved maximum compressive, tensile,

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and adhesive bond strength at a 20% replacement level. However, water demands rise rapidly beyond 20–40% replacement level due to the pore-filling effect of marble particles, which ultimately increases the dry shrinkage (Kabeer and Vyas, 2018). On the other hand, a reduction in compressive strength and an increase in water absorption coefficient and apparent density were reported by Lezzerini et al. (2022), replacing cement at 5–25% by mass with marble powder in cement mortar (Lezzerini et al., 2022). Vardhan et al. (2015) studied replacing marble powder with cement from 0% to 50% at a 10% increment in mortar mixes. Their study testified that mortar could achieve a 28-day compressive strength of 43 MPa and 41.67 MPa at 10% and 20% replacement levels, respectively. The reduction in compressive strength at a higher replacement level showed that marble powder acted only as a filler and did not significantly alter the hydration products (Vardhan et al., 2015; Singh et al., 2017). Further, studies were addressed to the use of marble powder in the production of concrete or mortar as influencing of the mechanical properties or the binding process or both (Rana et al., 2015; Xi et al., 2019) also, in this case not arriving exactly at the same results.

If several studies can be found in the literature about the use of marble powder, not the same can be stated for granite dust, whose use seems to be limited to partial substitution of fine aggregate [e.g. (Munir et al., 2017),]. This suggests that investigations addressed to understand if granite dust can assume a role in cement reactions should be done, circumstances currently not clarified.

Differently from granite dust, much more interest has been recorded in glass wastes (GW) by glass industries (Mármol et al., 2010; Shi and Zheng, 2007; Federico and Chidiac, 2009; Ismail and Al-Hashmi, 2009). An appropriate milling process of glass waste seems effective in the production of particles having a size influencing the pozzolanic activity (Shi et al., 2005) depending on the content of SiO_2 and Al_2O_3. Different attempts in this direction can be found in (Ismail and Al-Hashmi, 2009; Madandoust and Ghavidel, 2013; Adhikary et al., 2021; Tan and Du, 2013), not evidencing a univocal result and univocal approaches but having, as a primary goal, the resistance improving to compressive loading, surface scaling, chloride ions penetration, and freeze-thaw cycling (Mehta and Ashish, 2020; Tan and Du, 2013; Li et al., 2022; Kim et al., 2014).

In this frame, the study here presented aims to observe, from the mechanical and physical point of view, mortars characterized by a replacement of cement with Ground Glass Waste (GGW), Granite Powder (GP), and Ground Granite Powder (GGP), or characterized by a replacement of sand with Marble Powder (MP), in the direction of production of environmental low impacting mortars. Providing a contribution in the understanding of the influence of the chemical composition, particle size, and content of the materials before mentioned on blended mortars' mechanics, physical and microstructure properties at long-term curing is the goal of this study in the context of literature results not univocal or missing in some case, as for granite dust. The attention is focused on the chemical influence of GP, GGP, and GGW in the mix assumed as a partial substitute of cement providing data to be crossed with data available in the literature. On the other hand, the physical/mechanical support of MP is observed as a partial substitute of sand with the same aim to enrich and confirm literature results not always coherent.

2. Materials and methods

2.1. Materials and material characterization

The granite waste was collected from the sludge produced during sawing, cutting, and polishing of dimensional stones in the district of Peshawar of Khyber Pakhtunkhwa, Pakistan. Granite powder was ground for 2 min in a ring milling machine to check the effectiveness of small-sized particles on the pozzolanic activity in blended mortars. Glass bottles were cleaned before being crushed and powdered. After drying, the clean glass was smashed and ground using a ring milling machine.

The marble waste is the sludge produced while cutting and polishing marble stones inside the processing unit. The recycled waste materials after the milling process are shown in Fig. 1. The physical properties of the waste materials used for the blended mortar mixes are summarized in Table 1. The comparative particle size analysis was performed on granite powder, marble powder, and fine aggregate according to ASTM 136–01 (ASTM C136 -01, 2001), as shown in Figs. 2 and 3. The fineness modulus of fine aggregate was 2.33, which is in the range of 2.3–3.1 according to ASTM C33 (ASTM C33, 2003. The fineness modulus of granite powder was 1.55. Moreover, the fineness of Cement, granite, and marble powder was 1.34%, 70%, and 95%. The cement and fine aggregate density are 3.15 g/cm^3 and 2.63 g/cm^3. The particle size distribution (PSD) of GGW, GP, and MP was determined from 2 μm to 60 μm by a laser particle analyzer (Multisizer 3). This test automatically calculates the PSD's mean, mode, and standard deviation. The PSD standard deviation of GGW and GP was 2.973 μm and 3.039 μm, respectively. The PSD of GGW, GP, and MP is shown in Figs. 4 and 5. The particle size of GP, GGW, and MP is in the range of 2–20 μm, 2–30 μm, and 2–7 μm, respectively.

X-ray Fluorescence (XRF) was used to find the chemical compositions of Granite Powder (GP), Ground Granite Powder (GGP), and Ground Glass wastes. XRF results concluded that Ground Glass Waste (GGW) and Granite powder (GP) is pozzolanic materials because the combined percentage of SiO_2 and Al_2O_3 is more than 70%, as listed in Table 3. Glass waste (GGW) has higher SiO_2 and Na_2O but lower CaO than GP/GGP. According to ASTM C618-02, an excellent pozzolanic material should have a sum of $SiO_2 + Al_2O_3 + Fe_2O_3$ higher than 70%. The $SiO_2 + Al_2O_3 + Fe_2O_3$ for investigated GGW and GP/GGP are 77% and 75%, respectively. The raw materials (GGW and GP/GGP) present satisfactory chemical composition; therefore, the raw materials can be classified as Class N natural pozzolan and could produce a good pozzolanic reaction (Li et al., 2022). The raw materials have a particle size of 2–30 μm to assess the influence of fineness on the pozzolanic activity. High alkali content makes glass different from other wastes. The high content of Na_2O in finely glass powder can act as a catalyst making calcium silicate hydrate and promoting strength development (Khmiri et al., 2013). Marble powder (MP) contains sufficient CaO and SiO_2, which can be used as a binding material. The MP includes a high amount of calcite originating from limestone marble sawing. Its chemical composition is similar to limestone filler. The comparison between particle size distribution of Granite Powder (GP), Ground Glass Waste (GGW), and Marble powder (MPs) are plotted in Figs. 2 and 3. The scanning electron microscope (SEM) operated with an accelerating voltage of 20 kV, and a higher magnification level (>200X) was employed to examine the particle size and identification of phase composition based on qualitative crystalline structure or features of by-products, as displayed in Fig. 4. More comprehensive information about this testing method can be obtained from the reference (Hassan et al., 2021).

2.2. Mix design and sample preparation

The mortar mixtures containing Ground Glass Waste (GGW), Granite Powder (GP), and Ground Granite Powder (GGP) as a partial replacement of cement at varying ratios of 5%, 10%, and 15% by mass. Other blended mixtures were prepared by partially replacing fine aggregate with Marble powder (MP) at varying ratios of 10%, 20%, and 30% by mass. For adequate workability of blended mortars, the water-to-cement ratio of 0.50 was considered, and the cement-sand ratio of 1:6. The mortar strength is crucial as the bond strength between the masonry units is dependent on the strength of the mortar. First, control mortar samples (total number 12) were prepared using a cement-sand ratio of 1:6. Cube dimensions of 50 × 50 × 50 mm were prepared in two layers by giving 12 blows to each layer. Then the blended mortar was produced by adding pozzolanic material with a specific percentage of cement partial replacement. A total of one hundred and eight (108) cube

Fig. 1. Recycled waste raw materials after milling processing.

Table 1
Physical properties of raw materials.

Raw Materials	Physical Properties	
GGW	Colour Density	White 2.59 g/cm^3
GP/GGP	Colour Density	Grey 2.68 g/cm^3
MP	Colour Density Composition	White 2.60 g/cm^3 $CaCO_3$

samples were prepared for GGW, GP, and GGP-modified blended mortars. Similarly, a total of 48 cubes were prepared for MP-modified blended mortars. The detailed mix proportions for all batch mixtures are given in Table 2.

2.3. Methods

2.3.1. Compressive strength/strength activity index (SAI)

The compressive strength test was conducted per ASTM C-109 specification (A. C109/C109M – 11, 2013). The compressive strength was measured by a universal testing machine (UTM). The compressive strength test was performed on the 3rd, 7th, 28th' and 91st day and the average value of triplicate specimens is presented as the compressive strength at the specified curing age. The strength activity index (SAI) was also determined on the 7th, 28th, and 91st days to evaluate the strength development of control mortars and blended mortars containing pozzolanic materials. The strength activity index (SAI) was calculated according to the ASTM C311 specification (A. C311, 2013).

$$\text{SAI}\ (\%) = A/B \times 100$$

In the above equation, A and B represent the average compressive strength of the modified blended mortar and the control mortar, respectively.

2.3.2. Dry density

The dry density of blended mortars was determined on the 3rd, 7th, 28th, and 91st curing days. The average value of triplicate specimens is taken as the dry density at specified curing age according to ASTM C642-13 (A.I.J.A.B.o.A. Standards, 2013).

2.3.3. X-ray powder diffraction (XRD)

The X-ray powder diffraction (XRD) test was performed on the control and blended mortars modified with GGW, GP, and GGP as a partial cement replacement at 5%, 10%, and 15% by mass. The hydration process of blended mortar samples was ceased by acetone before conducting the XRD test. The test was conducted on the 3rd, 7th, 28th, and 91st day to evaluate the pozzolanic reactivity and to identify crystalline phases in mortar made with or without by-products. XRD patterns of all paste samples were recorded using the Cu radiation of wavelength 1.5405. The diffracted rays are detected between 2° and 65°

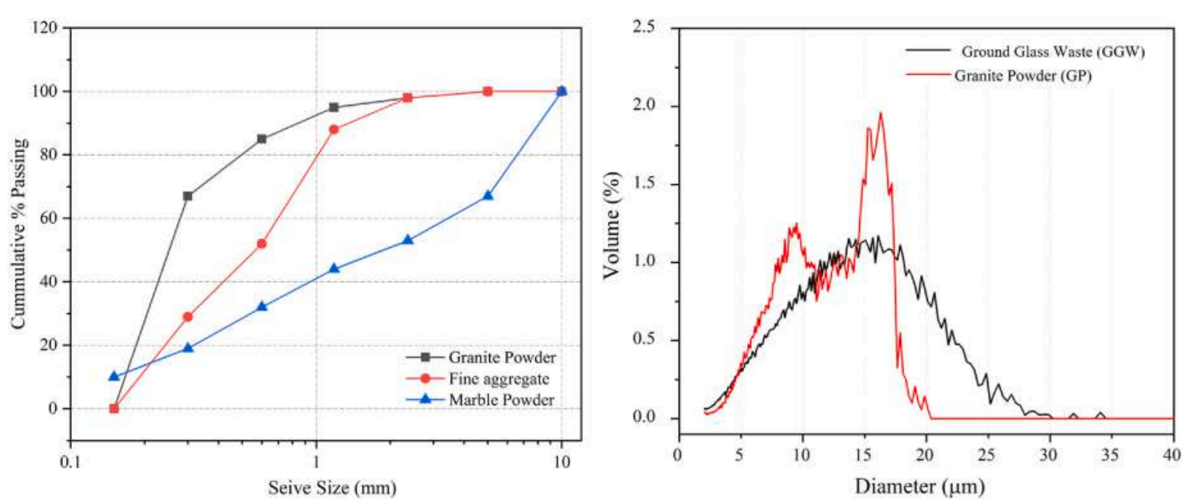


Fig. 2. Particle size distribution of waste materials.

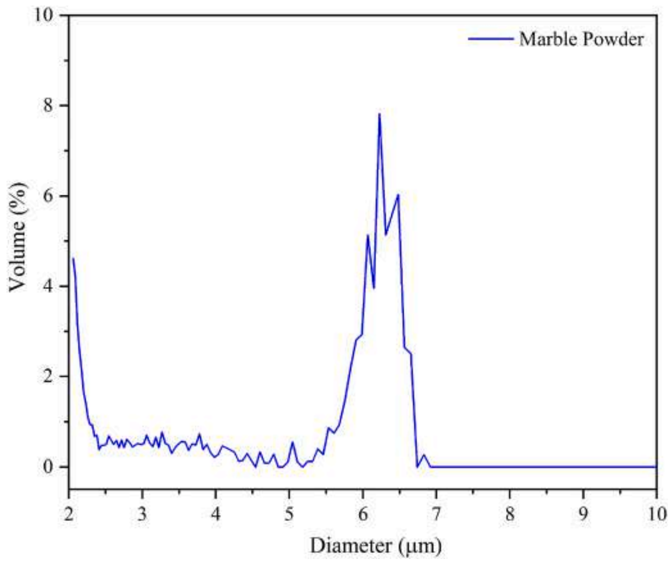


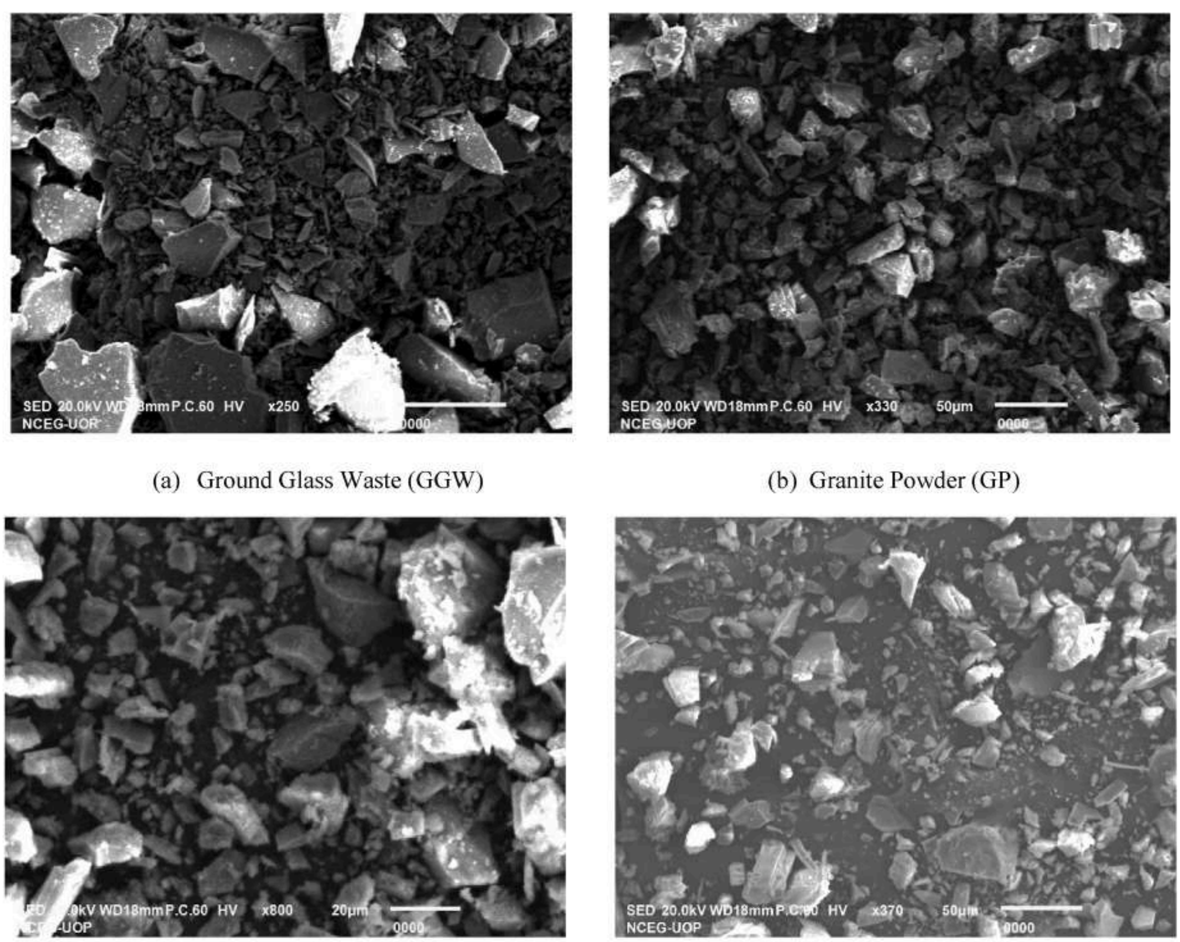
Fig. 3. Particle size distribution of Marble Powder (MP).

with a step size of 0.05 and a step time of 1 s. The peak intensities of calcium hydroxide $Ca(OH)_2$ and other hydration products of control mortar and modified blended mortars were compared at different curing ages.

3. Results and discussion

3.1. Compressive strength development and pozzolanic activity

To study the influence of Ground Glass Waste (GGW), Granite Powder (GP), and Ground Granite Powder (GGP) on the strength development of mortar, compressive strength tests were conducted at various curing ages, as shown in Fig. 5. From Fig. 5 (a), It can be noticed that the compressive strength of standard mortar on the 3rd and 7th days is greater than the blended mortars modified with GGW at all replacement ratios. The compressive strength of standard mortar on the 3rd and 7th days was 7.55 MPa, and 9.53 MPa, correspondingly higher than all other substitution ratios except GGW-10%, which attained similar 3rd-day strength as standard mortar. The blended mortars (GGW-5% & GGW-10%) achieved superior compressive strength at the later curing age of 28th and 91st days, which is even higher than standard mortar. Two trends were observed in the strength development of mortars modified with Ground Glass Powder (GGW). In the first trend from 3rd to 7th, a significant difference was observed in the strength; however, in the second trend from 28th to 91st, the strength difference became smaller due to the increased pozzolanic reactivity of SiO_2 and CaO of the glass powder in the pore solution. This observation agreed with the previous study (Elaqra and Rustom, 2018). Besides, the finely Ground Glass Powder (GGW) (Particle size <35 μm) exerted a positive effect on the compressive strength development of blended mortar at a later curing age, negating the strength decrement and fostering the high pozzolanic reactivity, which resulted in a significant consumption of



(a) Ground Glass Waste (GGW)

(b) Granite Powder (GP)

(c) Marble Powder (MP)

(d) Ground Granite Powder (GGP)

Fig. 4. SEM images of by-products used in this study.

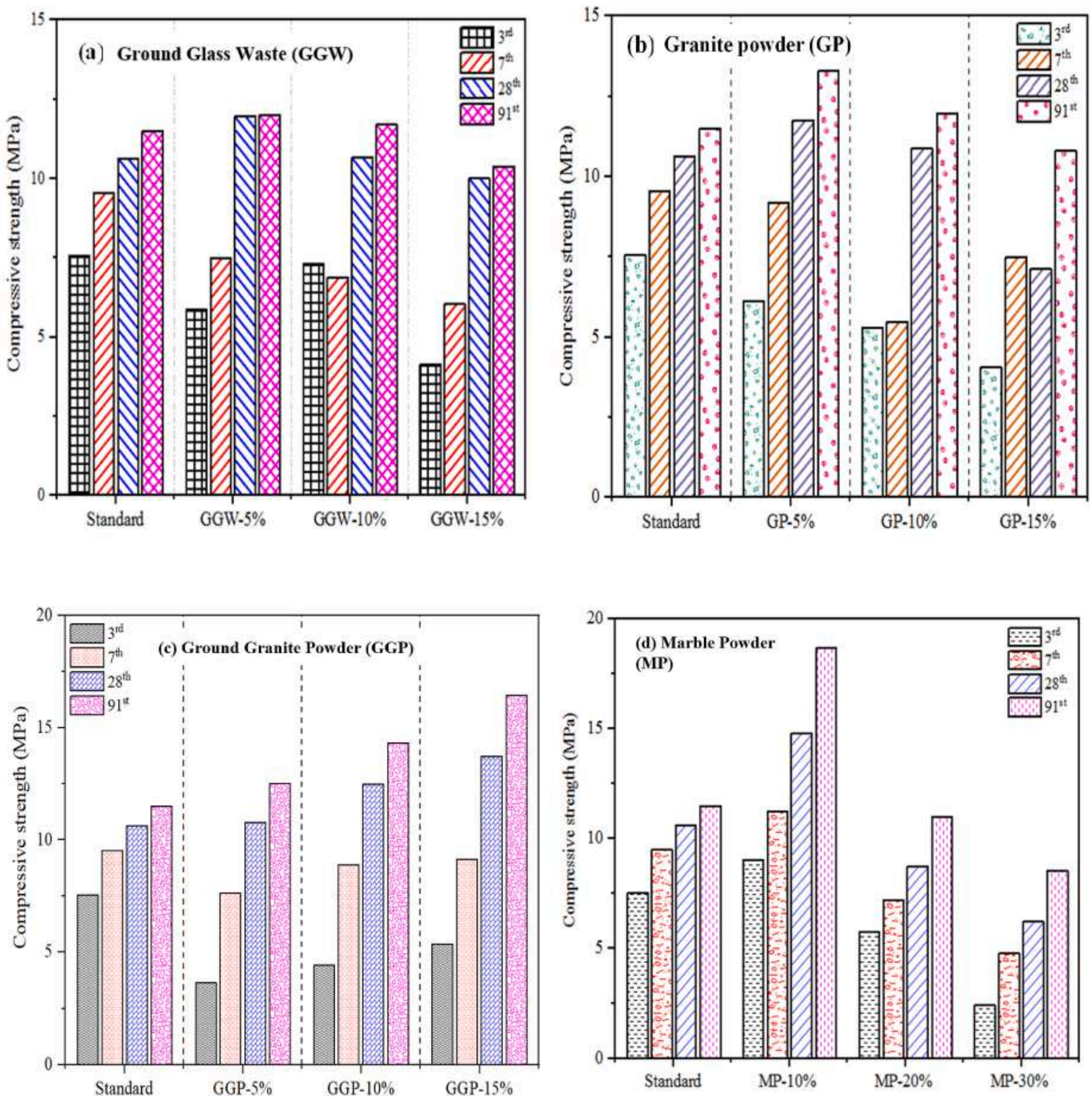


Fig. 5. Compressive strength development of blended mortars at different curing ages.

Table 2
Mix design for mortar mixtures.

Mix	W/C	Cement (%)	Sand (%)	GGW (%)	GP (%)	GGP (%)
Control mortar	0.50	100	100	–	–	–
GGW-5%		95	100	5	–	–
GGW-10%		90	100	10	–	–
GGW-15%		85	100	15	–	–
GP-5%		95	100	–	5	–
GP-10%		90	100	–	10	–
GP-15%		85	100	–	15	–
GGP-5%		95	100	–	–	5
GGP-10%		90	100	–	–	10
GGP-15%		85	100	–		15
MP-10%		100	90	–	–	–
MP-20%		100	80	–	–	–
MP-30%		100	70	–	–	–

Table 3
XRF results of GP/GGP and GGW.

Chemical composition (%)	GP/GGP	GGW	MP
SiO_2	56	72	42
Na_2O	4.2	19	3.6
Al_2O_3	15.05	5.34	18.06
MgO	4.75	0.63	2.78
CaO	9.0	5.28	51.40
K_2O	0	0.10	1.30
MnO	0.7	0	0
P_2O_5	0.09	0.01	0.01
Fe_2O_3	4.0	0.38	0
TiO_3	0.37	0.03	0

calcium hydroxide (Li et al., 2022; Afshinnia and Rangaraju, 2015; Shao et al., 2000; Carsana et al., 2014). As the partial substitution of cement with GGW increased from 5% to 15%, the compressive strength followed an increasing trend and then decreased. This enhancement in compressive strength development could be attributed to the pozzolanic reactivity of glass powder, promoting C–S–H formation and leading to a denser matrix microstructure (Kamali and Ghahremaninezhad, 2015). In addition, another reason is that Ground Glass Powder (GGW) with smaller particle size not only ensured a high pozzolanic reactivity but also offered an improved filling effect than cement (Wang et al., 2022). The compressive strength of GGW-5% at 28 days is 11.95 MPa compared to 10.63 MPa of standard mortar; thus, GGW-5% achieved 11% more compressive strength than standard mortar; however, a reduction in compressive strength at a higher substitution rate of GGW was observed. Fig. 5 (b) illustrates that generally with the ongoing curing times, the compressive strength of blended mortars showed improvement at all replacement ratios; however, with the rise in cement replacement ratio with Granite Powder (GP), a reduction in compressive strength was noted as compared to the control mortar. It is apparent from Fig. 5 (b) that up to 10% increment of GP substitutions induced no significant effect on the compressive strength of blended mortars at later curing ages. The compressive strength enhancement of blended mortar up to 10% GP substitution is associated with the filling effect of high fineness, forming a denser and compact matrix, this result is consistent with the previous study in (Rana et al., 2015). Beyond a certain limit, the further substitution of GP negatively influenced the strength of blended mortars due to less cement being available to bind the fine aggregate mix. In addition, the dilution of cementitious materials resulted in a poorly compacted porous microstructure because of excess water requirements for workability with a higher replacement ratio (Mashaly et al., 2018). According to Li et al. (2016), the reduction in strength can be explained by the lower cementing and binding efficiency of granite waste compared to cement, where the dilution effect of cementitious materials is dominant over the physical effects on improving the size distribution at a higher replacement ratio (Li et al., 2016). In contrast, the fineness of Ground Granite powder (GGP) significantly contributed to the improvement of compressive strength and hardened density of blended mortars at each substitution ratio, as shown in Figs. 5 (c) and Fig. 7(a). Furthermore, increasing marble waste (MP) replacement with sand reduced compressive strength; however, at 10% replacement, mortars prepared with MP demonstrated higher compressive strength than standard mortar mixes. The early age strength development of mortars with MP is anticipated due to the pore-filling effect, although this effect is limited at a lower substitution (Ashish, 2018; Kabeer and Vyas, 2018).

Fig. 6 shows the strength activity index of MP-modified mixes at different curing ages. The SAI of MP-modified mixes at 20% substitution exceeds the minimum requirements of ASTM C311 specification (A. C311, 2013). The filler effect of marble powder enriched mortar's cement matrix and packing properties. Therefore, the blended mortars

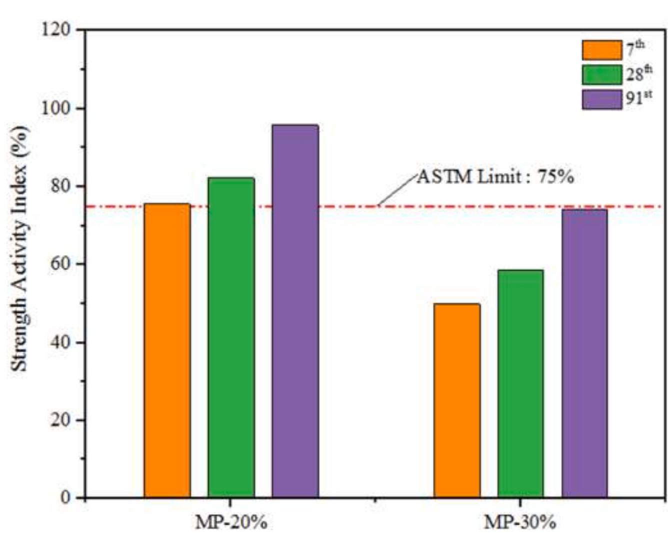


Fig. 6. Strength activity index (SAI) of Marble powder-MP mixes at different curing ages.

produced with Marble Powder (MP) as a sand replacement achieved the highest strength. The compressive strength of blended mortars (GGW-5% & GGW-10%, GP and GGP-5% & GP and GGP-10%, and MP-10%) reached more than 10 MPa at 28 days, greater than the minimum compressive strength required by different codes as the building code of Pakistan (Ministry of housing and works and I, 2007).

3.2. Hardened density

The hardened density of all blended mortars is primarily equal to or greater than the standard mortar, as shown in Fig. 7. The pore-filling effect of fine glass particles improves the mortars' cement matrix and packing density. The modified mortar mixes achieved a density of 2000 kg/m^3 at all curing ages at each substitution level. In addition, the density of all other MP mixes at 10% and 20% ratios are greater or equal to standard mortar. Greater packing density and compressive strength were achieved by blended mortars produced with a lower dosage of Granite Powder (GP), Ground Granite Powder (GGP), Ground Glass Waste (GGW), and Marble Powder (MP).

3.3. X-ray diffraction spectra

The XRD patterns of blended mortars produced with 5%, 10%, and 15% of Ground Glass Waste (GGW), Granite Powder (GP), and Ground Granite Powder (GGP) at the age of 3rd, 7th, 28th, and 91st are displayed in Figs. 8–10. The main crystal phases found in the Ground Glass Waste (GGW) samples are $Ca(OH)_2$, SiO_2, and Calcium silicate (C_3S & C_2S), as well as minor content of ettringite and $CaCO_3$, as shown in Fig. 8. The peaks of portlandite (CH) in the XRD spectra are observed at $2\theta = 18^{\circ\circ}$ (d = 4.9092 Å) and 34.10° (d = 2.6270 Å). It is evident that glassy or amorphous silica is the major constituent of pozzolanic materials, which reacts with calcium hydroxide and produced C–S–H gel in the matrix. The high pozzolanic reactivity of fine glass powder resulted in a significant consumption of calcium hydroxide, and the intake of $Ca(OH)_2$ in a paste demonstrates the degree of pozzolanic reaction (Afshinnia and Rangaraju, 2015). The heterogeneous nucleation effect and the pozzolanic reaction of glass particles could explain the variation in consumption of portlandite (CH) during the hydration process of OPC and fine glass powder. The heterogeneous nucleation effect could be dominantly responsible for yielding more portlandite during the early age hydration of OPC. At the same time, the pozzolanic reactivity consumed portlandite at a later age to form a gel product (Wang et al., 2022). To compare the peak intensity of $Ca(OH)_2$ at $2\theta = 18^\circ$ and 34.10°, the peak intensity of CH weakened as the fine GGW content increased, and the lowest possible peak intensity of CH was documented at a 15% GGW content. The rise in the GGW content with cement replacement triggers the reduction in the intensity of $Ca(OH)_2$ in the long-term curing. In addition, the peak intensity of C_2S and C_3S is assumed to be located at $2\theta = 32.60^\circ$ (d = 2.7445 Å); however, the peak intensity of C–S–H gel is weak in the XRD spectra and cannot be characterized accurately (Li et al., 2022).

The main mineralogical phases found in the blended mortar of Granite Powder (GP) included portlandite, calcite, and ettringite, products of cement hydration (Medina et al., 2017). Fig. 9 demonstrates the relative intensities of peaks in the XRD traces for the mortars produced with Granite powder (GP). The stronger peak intensity and high percentage of quartz are observed in granite-modified mortars during early-age hydration. This finding may be due to the high silica content of used granite powder, however, quartz intensities reduced at later curing ages. A qualitative examination of the XRD spectra showed that the diffraction lines for portlandite (CH) were less intense with the increase in granite powder content and curing age. However, no significant changes in the hydration products were noticed (Medina et al., 2017; AbdElmoaty, 2013).

Furthermore, the peaks of calcite ($CaCO_3$), quartz (SiO_2), calcium silicate hydrate or C–S–H ($Ca_6H_2O_{13}Si_3$), Calcium Aluminum Silicate

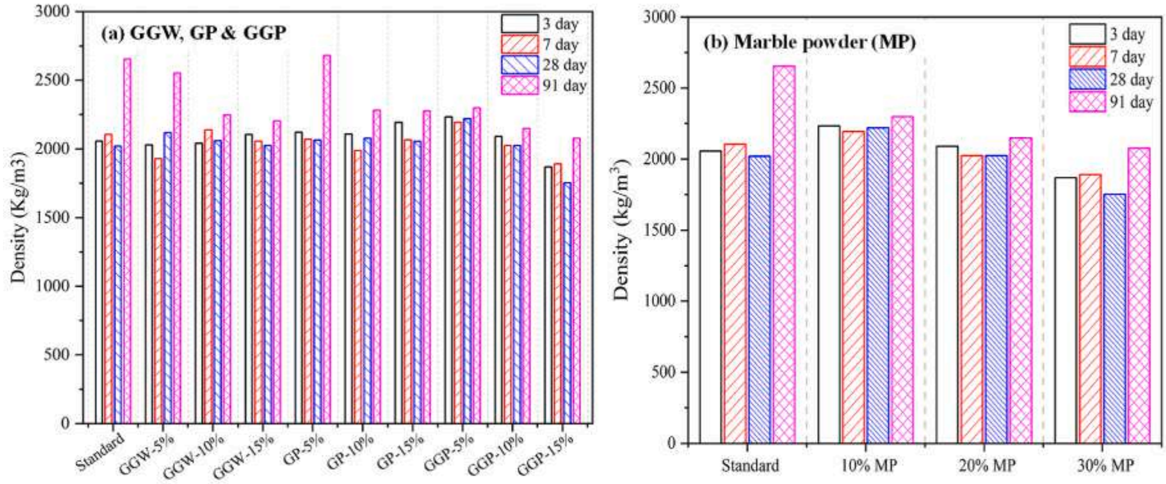


Fig. 7. Hardened density of blended mortars at different curing ages.

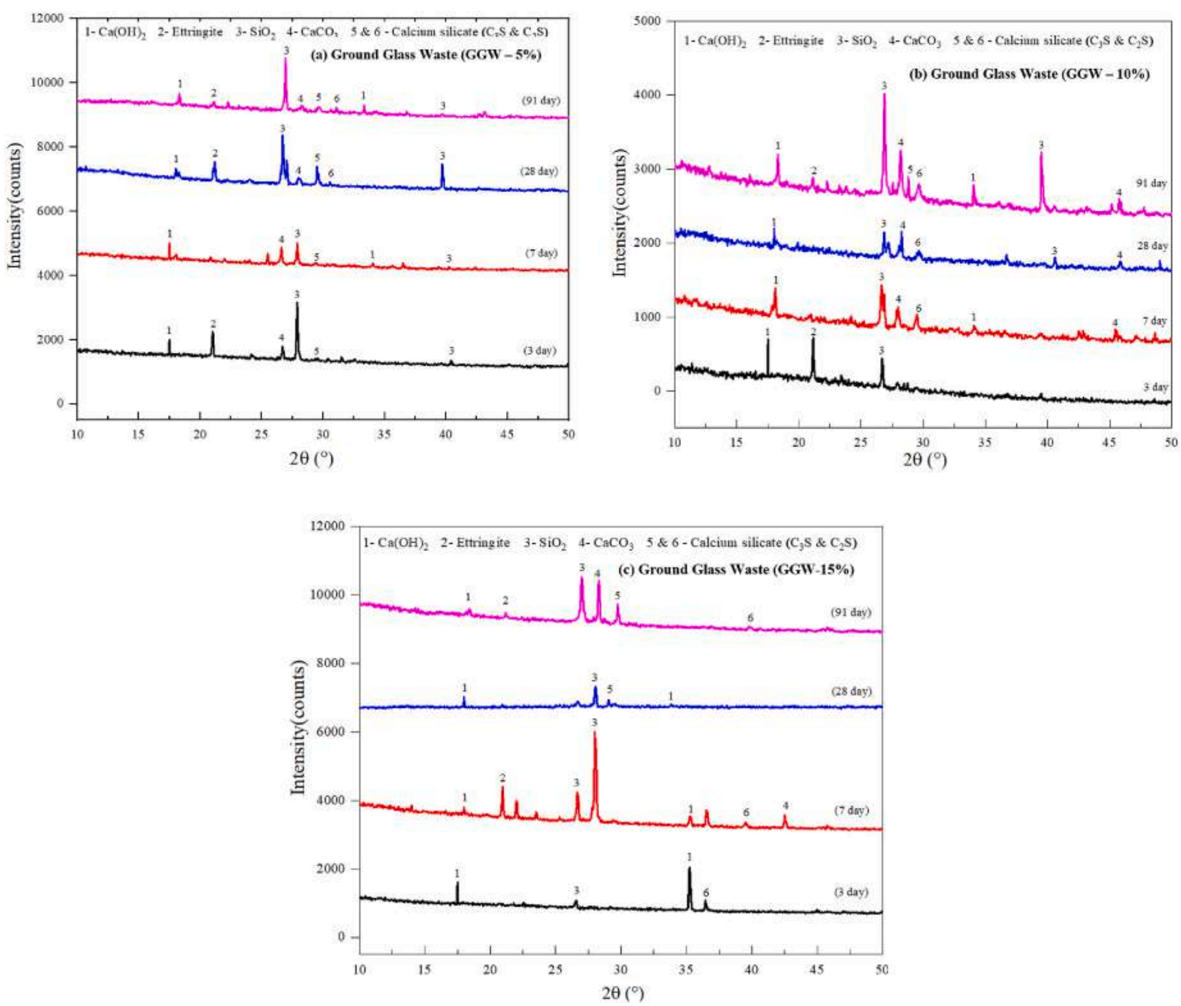


Fig. 8. XRD spectra of blended mortar modified with Ground Glass Waste (GGW) at different curing ages.

Hydrate (CASH), and portlandite ($CaOH_2$) were found in the Ground Granite Powder (GGP) mortars as presented in Fig. 10. X-ray diffraction patterns showed no apparent changes in the phase composition of fine Ground Granite Powder (GGP) and Granite Powder (GP) fillers. The only noticeable effect is that the low calcium hydroxide, ettringite, quartz, and calcite take effect as an inert filler material within the matrix, resulting in dense microstructure (Gautam et al., 2022; Jain et al., 2020b).

4. Conclusions

This study stems from the need to confirm the effectiveness of using

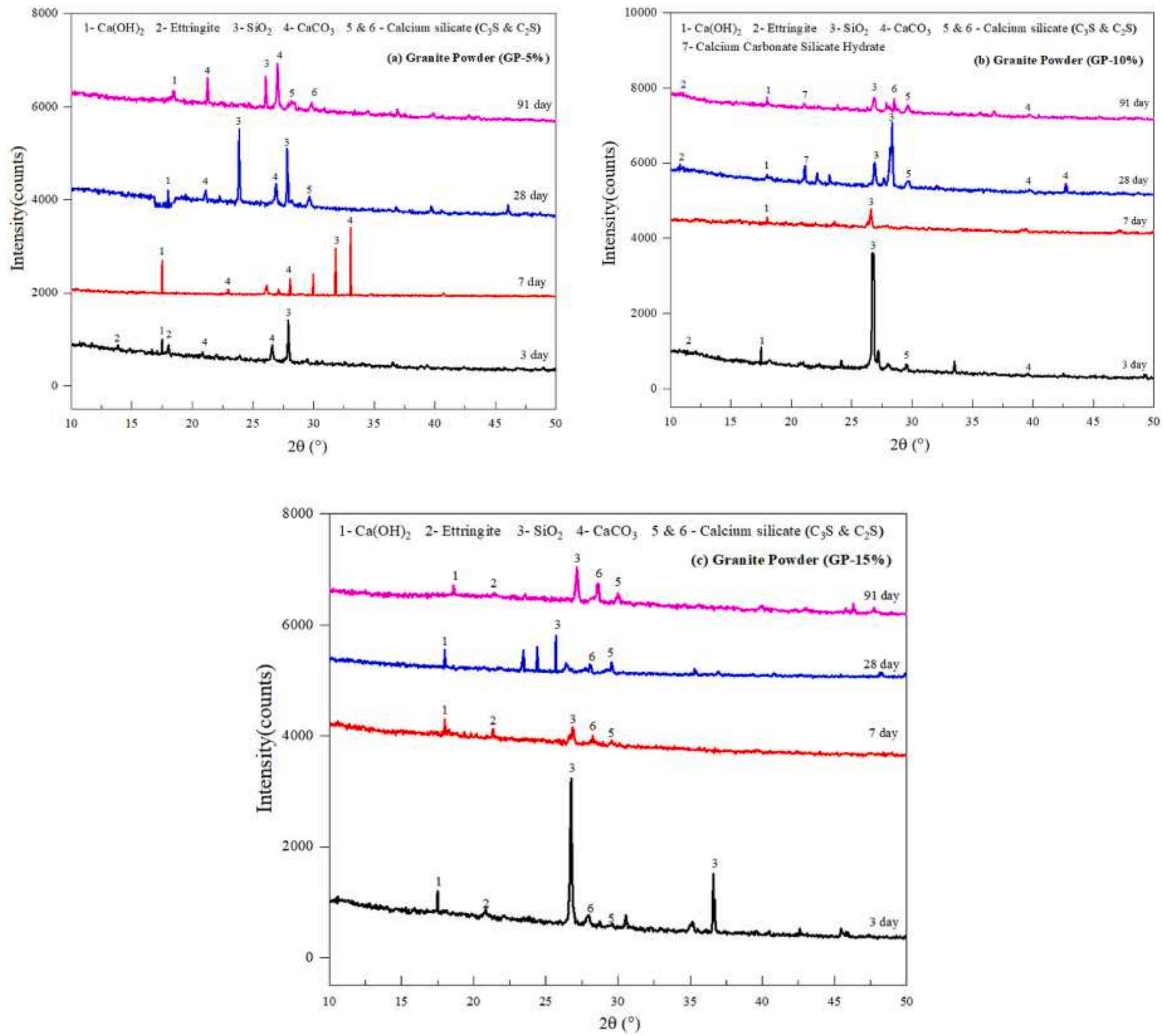


Fig. 9. XRD results of blended mortar modified with Granite Powder (GP) at different curing ages.

solid wastes for reducing their environmental impact and rationalizing by-products in cement-based mortars and to provide data to be added to those available in the literature not always univocal. Some fundamental aspects are discussed in this study that request to be more and more clarified and deepened by specific experimental campaigns necessary for the quality control of materials in connection to practical applications as well.

In details, this study assessed the feasibility of Ground Glass Waste (GGW), Granite Powder (GP), and Ground Granite Powder (GGP) as admixtures to replace cement and Marble Powder (MP) as a partial replacement for fine aggregate with different substitutions rates in mortar. The results supported the rationalization of solid waste valorization in cement-based mortars. The following conclusions can be drawn:

1. The fineness of Ground Granite Powder (GGP) considerably contributed to the enhancement of compressive strength and hardened density of mortar properties. The optimum percentage of Ground Glass (GW), Ground Granite powder (GGP), and Granite Powder (GP) that produced the maximum compressive strength and hardened density values are 10% and 5%, respectively. The pozzolanic effect of Ground Glass (GW) and Granite Powder (GP) is more evident at the later curing age of 28 and 90 days.
2. The substitution of natural aggregate with Marble Powder (MP) enhances the blended mortar's compressive strength and hardened density up to the replacement ratios of 10%, and the replacement ratio beyond optimum value reduces the mechanical properties of mortar.
3. The XRD results showed no significant changes in the mineralogical phase composition of the blended mortars except the variation in the portlandite (CH), proving in each of the cases studied the pozzolanic reactivity of Glass Powder, Granite Powder, and Ground Granite Powder.
4. Regarding Glass Powder, the results confirm many of the findings in the literature and nominate Granite Powder and Ground Granite Powder as effective materials in substituting cement for blended mortars.

Credit authorship contribution statement

Omer Farooq: Methodology, investigation, data curation, and writing—original draft. **Hassan Bilal:** Writing— original draft, review and editing, supervision & validation. **Liborio Cavaleri:** Conceptualization, validation, supervision, writing—review, and editing. **Alamgir Khan:** Visualization and software.

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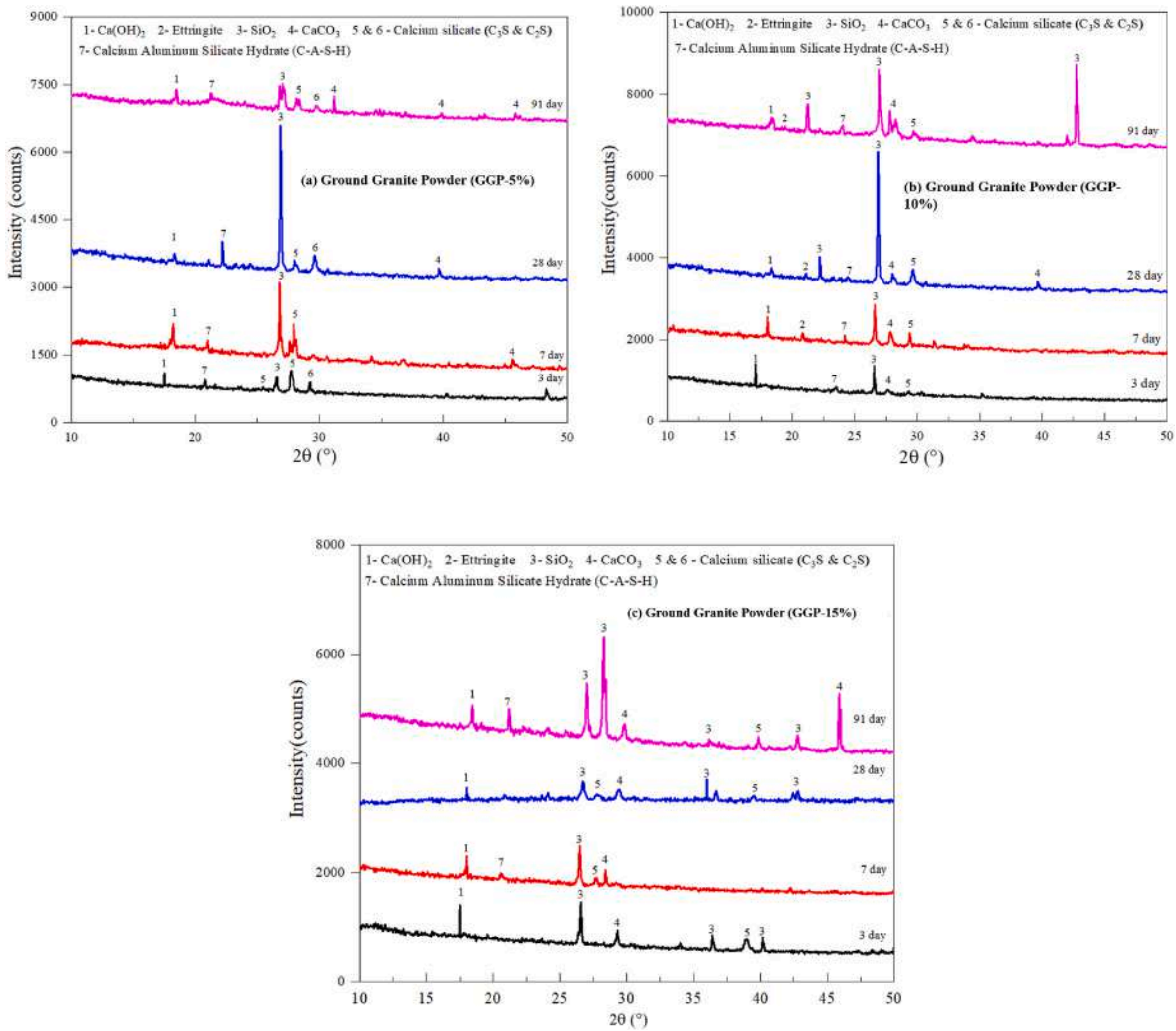

Fig. 10. XRD results of blended mortar modified with Ground Granite Powder (GGP) at different curing ages.

Data availability

No data was used for the research described in the article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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