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Performance assessment of industrial waste-based mortar under elevated temperatures

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Abstract:

The present study focuses on the effect of elevated temperatures i.e., 150, 300, and 450 °C on the mass and compressive strength of cement mortar consisting of industrial wastes such as plastic waste, micro silica, and ground granulated blast furnace slag. Plastic waste as a sand substitute and industrial by-products such as micro silica and ground granulated blast furnace slag as a cement substitute were used in the different mix proportions of cement mortar. The plastic waste with or without supplementary cementitious materials was used in the mortar mixes. The environmental assessment and performance index of different cement mortar mixes were evaluated and compared with the conventional mortar mix. Results showed that plastic waste, micro silica, and furnace slag enhanced the residual compressive strength, whereas the wastes reduced the mass of mortar specimens. It was concluded that the use of industrial waste up to a certain extent improved the performance of the mortar mixes. The circular economy and sustainable development are embodied in this approach by conserving natural resources, minimising waste, and maintaining acceptable performance characteristics.

Keywords:
plastic waste; industrial by-products; residual compressive strength; environmental assessment; performance index

1 Introduction

Fire causes a significant vulnerability to the integrity of concrete buildings, resulting in a noticeable reduction in their load-bearing capacity, and maybe even cause collapse. The multiphase and multicomponent composite material, fire, or high-temperature degradation of concrete involves a sequence of physical and chemical reactions. Concrete exhibits significant discrepancies in the thermal properties of the solid, liquid, and gas phases. The thermal expansion coefficients of the matrix and aggregate are dissimilar. Crack formation is facilitated by the presence of heat stress that exceeds the tensile strength of the concrete. When concrete structures are subjected to fire, they sustain significant damage, which immediately jeopardises building safety [1].

The significance of the technical characteristics of materials used in construction subjected to high temperatures was underscored by the fire-induced collapse of the World Trade Center in the United States in 2001, which resulted in a significant loss of life. Concrete is one of the most fire-resistant and thermally resistant construction materials. Extensive studies and practical experience have revealed that buildings made of concrete have a greater likelihood of surviving fires than those built using alternative materials. As long as the concrete is not heated over 300 °C, the pore size increases due to the degradation of calcium hydroxide ($Ca(OH)_2$) and calcium silicate hydrate (C-S-H). This is another significant factor contributing to decreased compressive strength at high temperatures [2].

Ground granulated blast furnace slag (GGBFS) is used as a cementitious material for the production of cement composites. Blast furnace slag (BFS) is a significant non-metallic industrial waste generated after iron ore is melted in a blast furnace. This industry also consumes significant amounts of energy and waste. Experimental evidence has shown that substituting a portion of cement with GGBFS can improve the longevity of concrete and decrease the excessive shrinkage and hydration heat in high-performance concrete [2].

In India, approximately 9.46 million tonnes of plastic waste (PW) are generated annually, with single-use packaging plastics accounting for nearly 43 % of the total. Despite national efforts, including a campaign to eliminate disposable plastics by 2022, approximately 40 % of PW remains uncollected and vast quantities pollute the environment, persisting for centuries without decomposing [3]. Therefore, effective management relies heavily on the reuse and recycling of plastics. Globally, approximately 300 million tonnes of plastic are produced each year, and since 1950, an estimated 8,3 billion tonnes of plastic have been generated, 60% of which have ended up in landfills or the natural environment [3]. Consequently, improper handling and treatment of PW poses serious risks to human health and ecosystems. Nonselective disposal and uncontrolled combustion of PW lead to significant environmental issues, such as the release of harmful air pollutants such as dioxins, furan, and particulate matter. It also causes an increase in microplastic and heavy metal levels in aquatic systems through degradation processes and a decrease in water permeability and soil fertility in agricultural fields [4]. The substantial surge in single-use PW has prompted researchers to prioritise the development of efficient, secure, affordable, and environmentally friendly approaches for immediate management. The potential of waste plastic as an eco-friendly and efficient substitute for natural coarse and fine aggregates in cement concrete production is supported by its desirable properties including low water adsorption capacity, corrosion resistance, low electrical and thermal conductivities, and high impact resistance. Additionally, it contributes to a circular economy [4].

Marof and Šiller, 2025 [5] studied the thermal insulation characteristics of cement mortar containing silica aerogel (3, 5, and 7 %) and recycled PET plastics (3 %). The results showed that the strength and setting time were within standard limits. The thermal conductivity of the mortar was reduced by up to 55 % compared with that of conventional mortar. Yıldırım and Tutkun, 2025 [6] examined CNC milling waste (CNCW) as a steel-fibre alternative in mortar exposed to 400-800 °C. CNCW improved the bonding, crack resistance, and overall thermal stability owing to its rough and irregular shape. The mortars with CNCW exhibited significantly better residual strength and performance, with increases of up to 70,74 % (compressive strength), 85,10 % (flexural strength), and 22,63 % (UPV) along with reduced mass loss.

Alexa-Stratulat et al., 2024 [7] observed that an increase in expanded perlite aggregates decreased the flexural and compressive strengths by up to 50 % and 30,71 %, respectively. Nevertheless, the dynamic moduli for replacement percentages of up to 20% were comparable to those of the reference mix. In contrast, the flexural strength values exhibited substantial improvements when exposed to temperatures of up to 200 ºC, with values of over 20% for temperatures of 150 and 200 ºC, and only marginal improvements in compressive strength, ranging from 3-20 % for temperatures of 150 and 200 ºC, when compared with those obtained at room temperature. Alkhrissat 2024 [8] reported that the compressive strength can be maintained by substituting 10 % natural sand with plastic sand and incorporating 20 % silica fume into the optimal mix. In conclusion, the results suggested that plastic aggregates can replace natural fine aggregates to produce environmentally safe mortars with comparable strength characteristics. Nasr et al., 2024 [9] examined the mechanical properties of 3D printed cementitious composites using hybrid recycled polypropylene and PET fibres. It was concluded that the hybrid combination improved performance compared to the individual sample. Owen et al., 2024 [10] investigated the mechanical and thermal performance of composites containing PW bottles reinforced with coated kenaf natural fibre. The results indicated that the mechanical and thermal properties improved because of the epoxy coating. This material is suitable for energy and building infrastructures.

Ding et al., 2023 [11] found that the bond and compressive strengths of mortar can be considerably enhanced by adding silica fume to the mortar, which plays a role in fine-particle infill and hydration gelation cooperation. The amount of added silica fume ranged from 0-10 %. The range of silica fume dosing from 0-4 % resulted in a slight increase in the thermal conductivity and dried density of the mortar, while the range of silica fume dosing from 4% to 10 % decreased once more. Silica fume has a beneficial effect on the fire resistance of insulating mortars. After 28 d of maintenance, the mortar with a 10 % silica fume admixture exhibited a relative compressive strength increase of approximately 14,73 % and a mass loss rate approximately 28,30 % lower after high-temperature treatment. Saeed et al., 2023 [2] showed that a greater exposure to heat and greater w/b ratios result in greater weight loss. The compressive strength of mixes containing GGBFS was at its highest at a temperature of 225 °C, while the compressive strength of mixes without GGBFS decreased as the temperature increased. The flexural strength of the mixes without GGBFS (w/b = 0,4) decreased as the temperature increased to 225 °C and subsequently to 625 °C. Conversely, the flexural strengths of the mixes containing GGBFS decreased as the temperature increased. Dong et al., 2022 [12] studied the fresh and hardened properties of self-compacting concrete consisting of plastic fibre waste and industrial waste, that is, fly ash, silica fume, and recycled concrete aggregate. It was found that the industrial waste significantly improved the fresh properties. The combination of plastic fibre and waste notably improved the mechanical properties. When subjected to elevated temperatures, Islam et al., 2022 [13] documented reductions in compressive strength of 10,8 % at 100 °C and 34,0 % at 200 °C. Rohden et al., 2020 [14] studied the efficacy of heat-induced concrete spalling enhanced by the inclusion of PW. The mechanical performance of the plastic in concrete was enhanced by 6,0 kg/m^3 after exposure to high temperatures. However, the mechanical properties were comparable to those of the reference concrete when 3,0 kg/m^3 plastic was incorporated. At higher temperatures, Saxena et al. 2018 [15] observed diminished residual compressive strength at both 300 and 600 °C in concrete where 5-20 % of fine and coarse aggregates (by volume) were substituted with PET aggregates. Liguori et al., 2014 [16] reported that composite mortars incorporating 10%–20% recycled aggregate in place of silica powder showed effective interaction between the plastic filler and mortar matrix, even without chemical modification. Studies have reported that this interaction helps reduce negative effects on physical and functional properties, particularly thermal degradation and fire resistance. Further deterioration was noted by Correia et al. 2014 [17], who reported decreased residual compressive strength in concrete incorporating PET flakes and pellets after exposure to 600 and 800 °C.

At the beginning of the twenty-first century, there were approximately 8 million fires worldwide. Hence, it is crucial to consider the significant impact of fire on the performance of cement-based materials, including physical damage and chemical modification. By considering this, the present study aimed to explore the influence on the performance of the mortar under the exposure of temperatures at 150, 300, and 450 °C. Industrial wastes such as PW (0, 3, 6, and 10 %), ground granulated blast furnace slag (10, 20, 30, and 40 %), and micro silica MS (5, 10, 15, and 20 %) were used to study the changes in mass, residual compressive strength, and colour of the different mortar mixes. An environmental assessment in terms of energy consumption and carbon dioxide emissions was evaluated.

The novelty of the present work is to examine the performance of different wastes, that is, PW, GGBFS, and MS, individually and in combination, in cement mortar exposed to high temperatures. PW was used as sand substitution; GGBFS and MS were used as cement replacements at different proportions in the cement mortar mixes and exposed to different temperatures i.e., 150, 300, and 450 °C for a duration of 90 min and compared with the conventional mix at room temperature. Environmental assessments of the different wastes in cement mortar have not been extensively explored. This study not only examined the mechanical performance at elevated temperatures, but also included mass loss analysis, SEM microstructural evaluation, and an environmental impact assessment (EIA) to provide a holistic understanding of performance and sustainability. As per author knowledge, this combination of materials, performance parameters, and analytical techniques has not been collectively addressed in previous studies, and thus provides new insights and practical contributions to the field.

2 Methodology

2.1 Materials

The present work used ordinary Portland cement (OPC) of grade 43 conforming to IS:8112-1989 [18] with a consistency of 29 %, fineness of 4 %, specific gravity of 3,15, and crushed sand as per IS:383-2016 [19] with zone II and fineness modulus of 2,76. The use of OPC grade 43 in this study was a deliberate choice based on its moderate hydration rate, lower heat evolution, and better dimensional stability compared with OPC grade 53, particularly under elevated temperature conditions. The use of OPC 43 provides a balanced and representative matrix for assessing the synergistic effects of waste materials rather than maximising the early strength. The PW was obtained from a local plant where PET bottles were crushed into finer sizes. The PW was obtained by shredding the plastic bottle waste. The PW used in this study consisted of irregularly shaped shredded flakes with an average length of 5-15 mm, width of 3-10 mm, and thickness of 0,2-1,0 mm. The material was sourced from postconsumer packaging waste and cleaned prior to use. The plastic particles were blended with natural sand in controlled proportions to maintain a suitable particle size distribution, and the staged and prolonged mixing procedure ensured uniform dispersion and minimised segregation. No chemical pre-treatment or surface modification was applied to the crushed PET particles. The mechanical interlocking provided by the rough surfaces of the crushed PET and the densification effect of supplementary cementitious materials (GGBFS and MS) were relied on to enhance the bonding between the plastic particles and the cement paste. The GGBFS and MS, which fill the micro-voids around the particles and improve the interfacial transition zone (ITZ), were procured from a local supplier. The MS was grey with 7,40 % particle size of 45 μm and specific gravity of 2,06. The GGBFS was off-white with a fineness of 2.2 and a specific gravity of 2,87. The chemical compositions of the cement and industrial wastes are listed in Table 1. Images of the cement and industrial wastes are shown in Figure 1. The SEM micrographs for the cement, GGBFS, MS and PW are shown in Figures 2a), b), c) and d), respectively. Irregular particles are observed in the SEM micrographs.

Table 1. Chemical properties of materials used

Materials	Oxides							
	CaO	SiO_2	Al_2O_3	Fe	MgO	Na_2O	K_2O	Loss on ignition
Cement	60,30	21,43	5,90	4,80	2,65	0,65	1,10	---
GGBFS	35,38	35,20	18,80	1,30	6,93	0,58	---	0,20
MS	---	90,00	---	---	---	0,87	---	2,65


a) cement b) PW

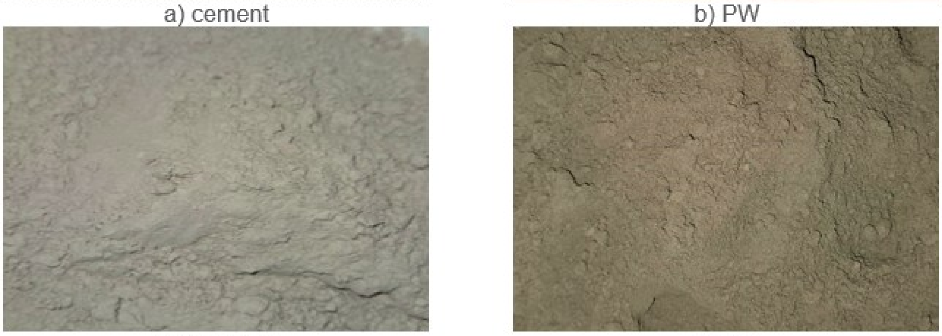
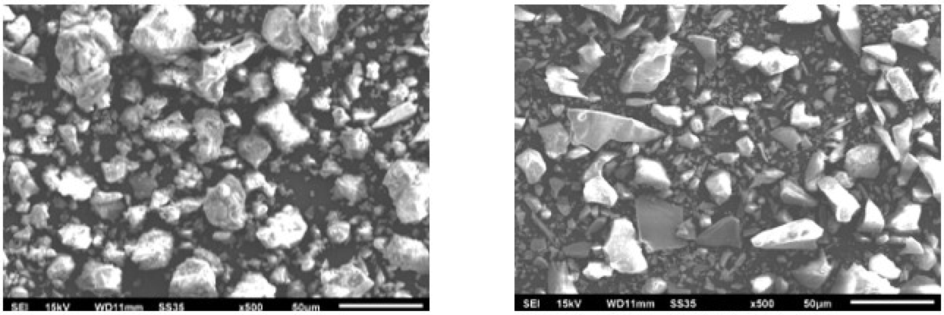
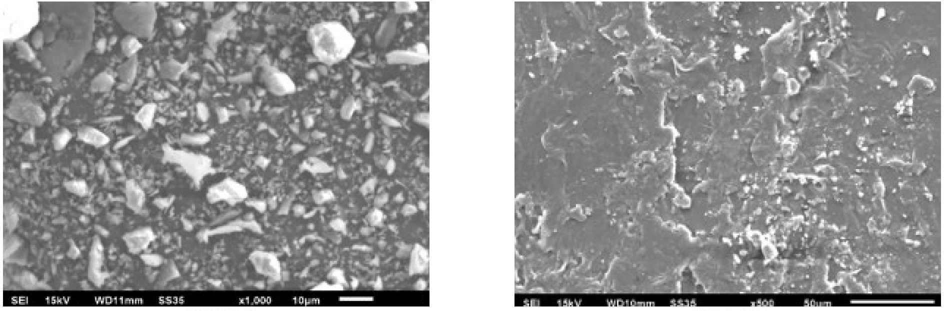

c) GGBFS d) MS

Figure 1. Images of cement, PW, GGBFS, and MS



a) cement b) GGBFS



c) MS d) PW

Figure 2. SEM images of cement, GGBFS, MS, and PW

2.2 Mixture design

The cement mortar experiment was conducted according to established standards. The mortar mixtures were prepared with a cement–sand ratio of 1:3 and a water-cement ratio of 0,43 [20; 21]. A higher cement content ensures an adequate paste volume to coat all aggregates, fill voids, and promote proper bonding, thereby compensating for the weaker interfacial transition zone caused by plastic inclusion. The range of PW replacement used in this study was selected based on findings reported in the literature, where several studies have explored replacement levels of up to 10 % [20-23]. The PW was used as a sand substitute at 0, 3, 6, and 10 % in the mortar mix. GGBFS was used to replace cement in the mortar mixes with substitution rates of 10, 20, 30, and 40 %, as was MS with substitution rates of 5, 10, 15, and 20 %, as listed in Table 2. All quantities of materials in the mortar mixes are in kg/m^3. Cube specimens of size 70,6 x 70,6 x 70,6 mm were cast from the various mortar mixes according to IS: 4031-1988 (Part-6) [24].

Table 2. Mix designation of different mortar mix proportions (kg/m^3)

Mix No.	Cement	Sand	Water	PW	GGBFS	MS
PW0	575,00	1725,00	247,25	0,00	0,00	0,00
PW3	575,00	1673,25	247,25	51,75	0,00	0,00
PW6	575,00	1621,50	247,25	103,50	0,00	0,00
PW10	575,00	1552,50	247,25	172,50	0,00	0,00
MS5	546,25	1725,00	247,25	0,00	0,00	28,75
MS10	517,50	1725,00	247,25	0,00	0,00	57,50
MS15	488,75	1725,00	247,25	0,00	0,00	86,25
MS20	460,00	1725,00	247,25	0,00	0,00	115,00
GGBS10	517,50	1725,00	247,25	0,00	57,50	0,00
GGBS20	460,00	1725,00	247,25	0,00	115,00	0,00
GGBS30	402,50	1725,00	247,25	0,00	172,50	0,00
GGBS40	345,00	1725,00	247,25	0,00	230,00	0,00
PW3MS5	546,25	1673,25	247,25	51,75	0,00	28,75
PW3MS10	517,50	1673,25	247,25	51,75	0,00	57,50
PW3MS15	488,75	1673,25	247,25	51,75	0,00	86,25
PW3BS10	517,50	1673,25	247,25	51,75	57,50	0,00
PW3BS20	460,00	1673,25	247,25	51,75	115,00	0,00
PW3BS30	402,50	1673,25	247,25	51,75	172,50	0,00
PW3BS40	345,00	1673,25	247,25	51,75	230,00	0,00

2.3 Test procedure

To examine the effect of elevated temperatures on the compressive strength of the mortar mixes, the cubic specimens were exposed to different temperatures in a muffle furnace and subsequently naturally cooled to room temperature. Before exposure to high temperatures, the specimens were withdrawn from the curing tank after 28 days of water curing and then dried [25; 26]. The specimens were subjected to three different temperatures 150, 300, and 450 °C for a duration of 90 min with a heating rate of 10 °C/min. The masses of the mortar specimens consisting of different waste materials were measured before and after heat exposure. A destructive compressive strength test was conducted on the exposed mortar specimens using a compression testing machine in accordance with IS:4031-1988 (Part-6) [24] and the results were compared with those of the unexposed or unheated specimens. Visual changes in the mortar specimens were observed and compared. Microstructural analysis was performed using SEM and energy-dispersive X-ray spectroscopy (EDS) [25]. The ecological (embodied energy (EE) and CO_2 emission (ECO_2)) aspects were considered in order to evaluate the environmental impact of mortar consisting of waste at different proportions. The values of EE and ECO_2 for the various materials used in the mortar mixes were obtained from literature [25; 27] and are listed in Table 3. The final ecological value of the different mortar mixes with different waste materials were calculated using Equation 1:

$$EE/ECO_2/Cost = \Sigma g_i m_i \tag{1}$$

Table 3. Value of EE and ECO_2

Materials	EE (MJ/kg)	ECO_2 ($kgCO_2/kg$)
Cement	5,500	0,9160
Sand	0,080	0,0040
Water	0,010	0,0000
PW	84,000	2,1500
GGBFS	1,600	0,0860
MS	0,036	0,0028

The efficacy of the additives in concrete can be described quantitatively rather than qualitatively. The performance of plain concrete was considered to be 1,0. Therefore, the performance of the concrete with additives was either less than or greater than 1, indicating that it was either inferior or superior to a plain mix in various respects. The efficacies of the additives, including PW, MS and GGBFS were assessed in comparison with that of a control mix [28].

3 Results and discussion

3.1 Visual change

The change in the colour of specimens exposed to elevated temperatures was investigated in the present study. An increase in temperature changed the colour of the specimens, as shown in Figure 3a). There was a slight or insignificant change in the colour of the specimens with different mix proportions. Following exposure there was a significant change in colour from grey to brown, as shown in Figure 3b). PW in the mortar began to soften, resulting in slight deformation and the formation of microvoids within the matrix. This had no negative impact on the strength of the mortar at 150 °C. Evaporation of water occurred at this temperature, which was observed through the mass loss. However, GGBFS and MS contributed to refining the pore structure, partially compensating for the plastic softening effect. Improved internal bonding owing to the pozzolanic reaction products (C–S–H gel) helped maintain integrity and improved strength. At 300 °C, the plastic components began to undergo thermal decomposition and gas release, leading to increased porosity and microcracking in the mortar. This reduced the bonding efficiency between the cement paste and aggregates, causing a noticeable decline in compressive strength [29]. The colour of the specimens changed from grey to brown, as shown in Figure 3. The GGBFS and MS continued to improve the residual strength by forming a denser C–S–H matrix and reducing free $Ca(OH)_2$. However, the voids left by the melted plastics reduced the load-bearing area, leading to a 20-30 % strength loss. Visual and physical changes include darkening of the surface, minor cracking, and mass loss. At 450 °C, most plastic materials were completely decomposed or volatilised, leaving behind voids that significantly weakened the mortar structure. In addition, the cement hydration products, particularly C–S–H and portlandite ($Ca(OH)_2$), started to dehydrate, which further accelerated strength loss. As a result, mortars containing PW exhibited a substantial reduction in mechanical performance and surface integrity beyond this temperature. PW completely decomposed, leaving voids that significantly reduced density and mechanical strength. Dehydration of C–S–H and $Ca(OH)_2$ decomposition began around 400-450 °C [29]. Although

GGBFS and MS help to form a more thermally stable gel structure, their benefits are outweighed by the plastic loss and microcrack propagation. Strength reduction could exceed 40-60 %, depending on the plastic content. In terms of overall performance, GGBFS and MS improved the residual strength retention and reduced the spalling tendency, but plastic substitution still limited the high-temperature performance.

a) b)

Figure 3. Mortar mix containing plastic: a) before exposure to high temperature, and b) after exposure

3.2 Mass loss

The influence of elevated temperatures on the mass of the mortar specimens containing of PW as a sand substitute and mineral admixtures (i.e., GGBFS and MS as cement replacements) was studied experimentally. Figure 4 shows the change in the mass of the various specimens with temperature. The mass losses of the various mix proportions increased with increasing temperature. In other words, an increase in temperature was observed to reduce the mass of the mortar mix specimens. The reduction in mass may be due to the evaporation of water from the matrix and the formation of air voids with increasing temperature [25]. The reason for the reduction in the mass loss of the specimen was the evaporation of water from the gel pores and small capillary pores. This, in turn, resulted in a substantial shrinkage of the specimens [2]. The mass loss at 150 °C was less than that at higher temperatures owing to the evaporation of free water, capillary water, and decomposition of ettringite [30]. The mass loss at 300 and 450 °C may be due to the release of water in C-S-H and the decomposition of C-S-H. The mixes with SF and GGBFS exhibited a higher mass loss, which may be due to their pozzolanic reaction that formed the C-S-H gel [31]. The mass loss increased with increasing temperature, which may be attributed to the release of physically or chemically bound water from the mortar specimens.

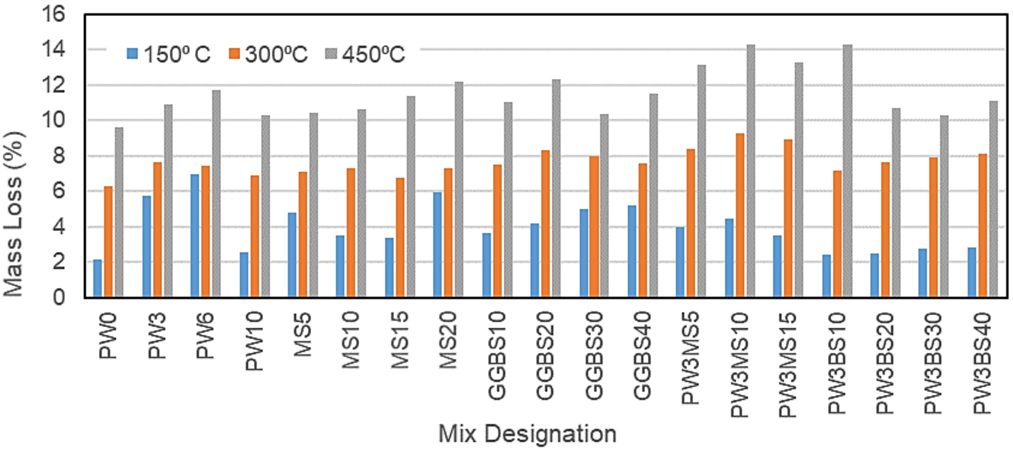


Figure 4. Variation of mass loss for the different mortar mixes

Figure 4 shows the mass loss of the different mix proportions and indicates that the mass loss of the materials containing industrial waste was higher than that of the control mix. The minimum and maximum mass losses were 2,0-6,0 %, 6,3-9,3 %, and 9,0-14,0 % at 150, 300, and 450 °C for the different mix proportions.

3.3 Residual compressive strength

Figure 5 illustrates the compressive strength of the mortar specimens consisting of various wastes at different proportions subjected to elevated temperatures of 150, 300, and 450 °C and compared with the specimens at ambient temperature i.e., room temperature. An increase in the compressive strength of the mortar was observed with an increase in temperature upto 300 °C, whereas the residual strength decreased on increase the temperature beyond 300 °C. The increase in strength up to 300 °C may be due to the narrow configuration of the hydrated cement paste after the evaporation of free water, resulting in greater Van Der Waals forces and the formation of additional hydration products. At 450 °C, the reduction in residual strength of mortar mix was observed might be due to the decomposition of C-S-H. The PW has positive effect by maintaining the integrity against the elevated temperature up to 300 °C [14]. The reduction in the strength of mortar containing industrial byproducts may be attributed to the dehydration of cement hydrates, decomposition of aggregates, and thermal incompatibility between the behaviour of aggregates and cement paste [30]. The loss in the compressive strength of mortar containing GGBFS may be attributed to the reversal of pozzolanic reactions owing to the loss of water from the paste, resulting in the dissociation of $Ca(OH)_2$ and a reduction in compressive strength [31]. A more gradual reduction in compressive strength was observed because of the presence of more voids owing to the rough texture and irregular surface. The presence of pores provides a pathway for the decrease in pore pressure caused by thermal effects under exposure to elevated temperatures, resulting in less decomposition of the matrix structures, and hence, a lower reduction in compressive strength [30]. After exposure at 450 °C, there was a reduction in the residual compressive strength. The compressive strength degradation rate of the cement mortar after heating was measured as the ratio of the compressive strength of the specimens after heating to that before heating [32]. The residual compressive strength varied from 12,44-32,70 MPa at 150 °C, 15,60-40,13 MPa at 300 °C, and 10,20-28,70 MPa at 450 °C, as illustrated in Figure 5.

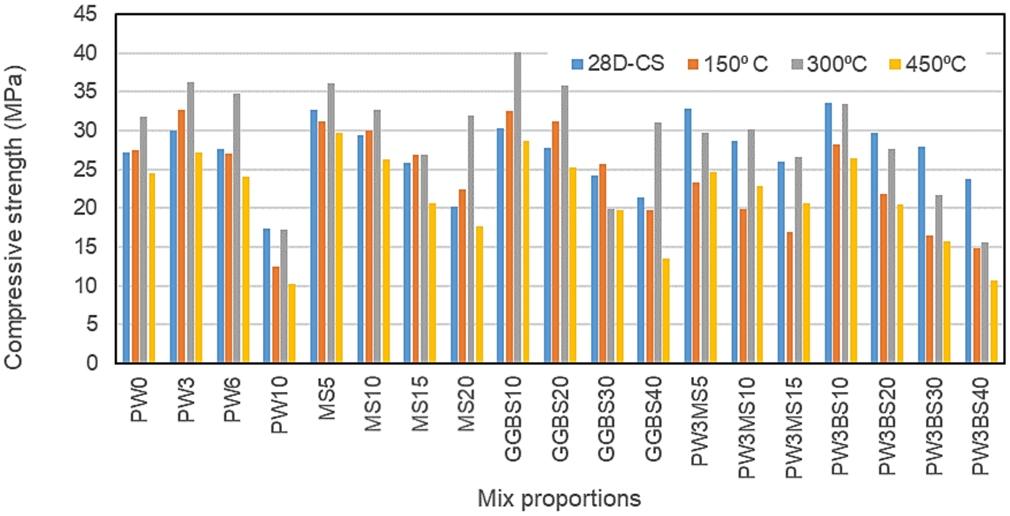


Figure 5. Effect of industrial wastes on residual compressive strength

Figure 6 shows the variation in compressive strength with respect to the control mix at different temperatures. The PW, MS and GGBFS increased the residual compressive strength by 1-19 %, 9-13 %, and 13-18 % at 150 °C, 9-14 %, 3-13 %, and 24-26 % at 300 °C, and 11 %, 7-21 %, and 3-17 % at 450 °C in the mortar mixes.

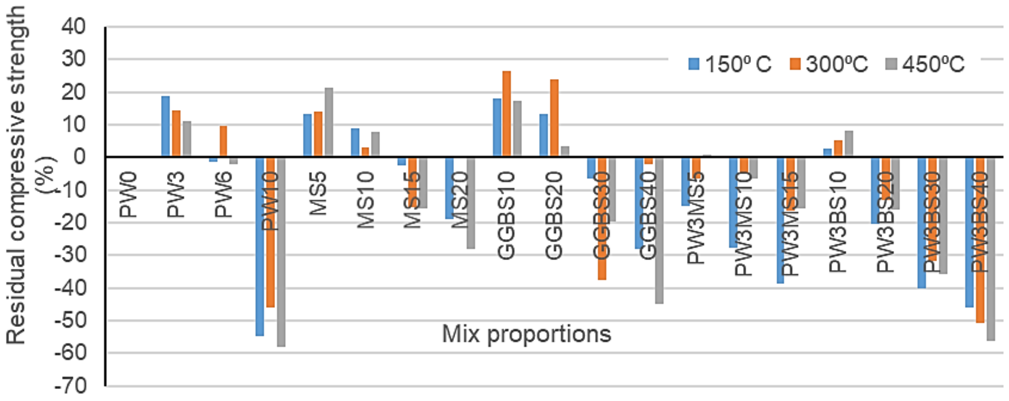
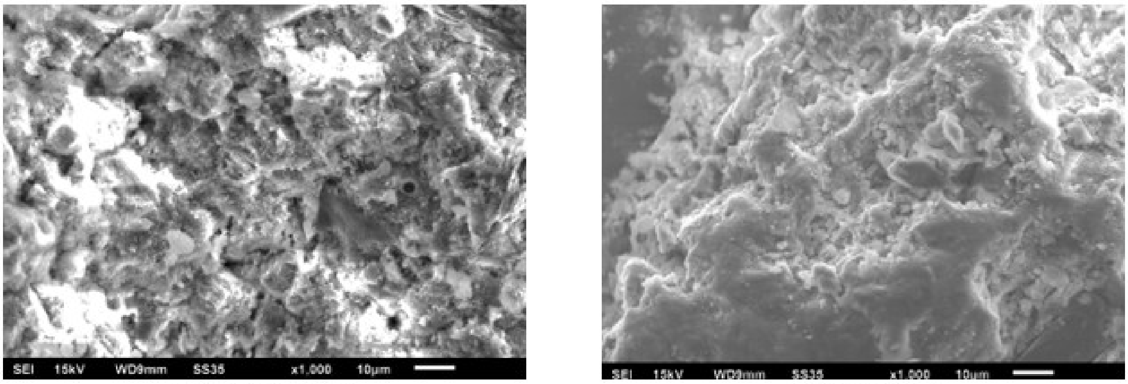


Figure 6. Variation of residual compressive strength with reference to control mix

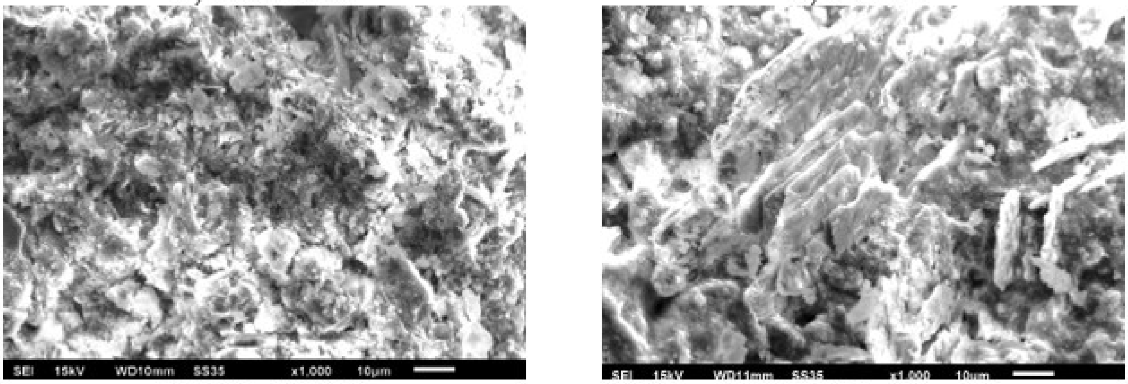
3.4 Microstructural characterization

Microstructural characterisation of the optimum mix proportions of the cement mortar was performed to correlate with the macro study. The optimum content of each additive individually such as PW (3 %), GGBFS (10 %) and MS (5 %) and their combinations i.e., 3 % PW + 5 % MS and 3 % PW + 10 % GGBFS was taken for the micro graph study at 300 °C and compared with the control mix as shown in Figure 7. Figures 7b), c), and d) show that the inclusion of PW, GGBFS, and MS densified the matrix, which was observed in the SEM micrographs, and validate the residual compressive strength experiment. At 300 °C, microcracks and voids appeared in all specimens; however, the control mix showed larger cracks and voids.

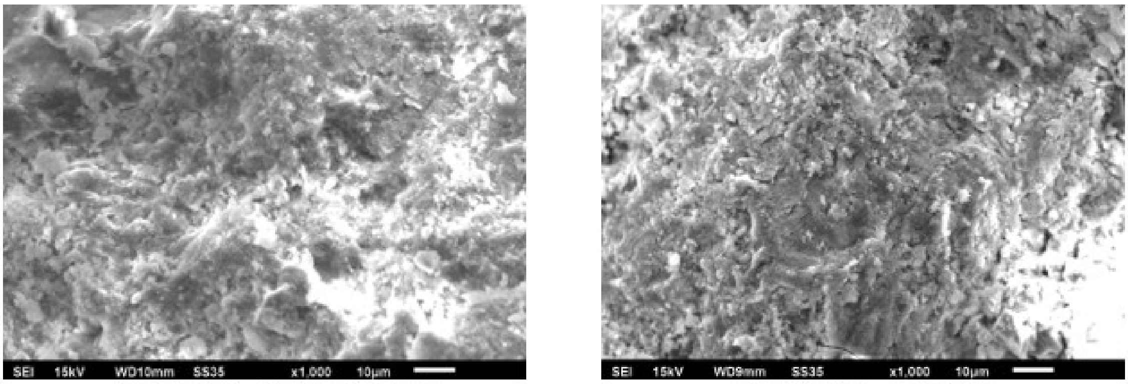
EDS revealed the elemental composition of what appears to the cement-based samples, as presented in Figure 8. The major elements were Ca and Si, which showed silicate phases and a strong presence typical of calcium silicate hydrates and calcium hydroxide in the matrix.



a) control mix
b) 3 % PW



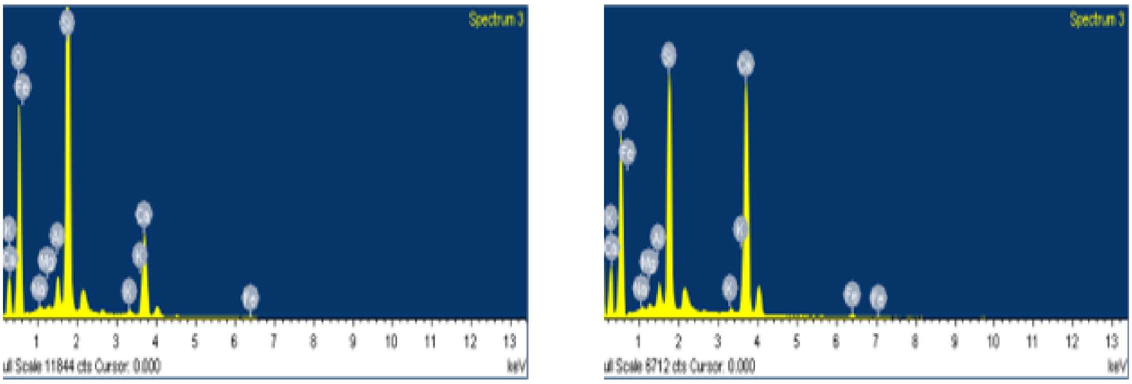
c) 10 % GGBFS
d) 5 % MS



e) 3 % PW+ 10 % GGBFS

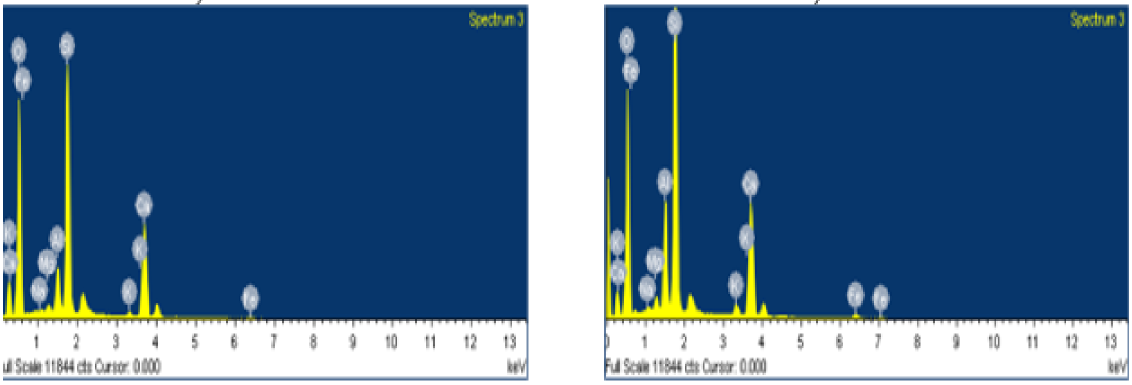
f) 3 % PW+ 5 % MS

Figure 7. SEM micrographs of different mix proportions



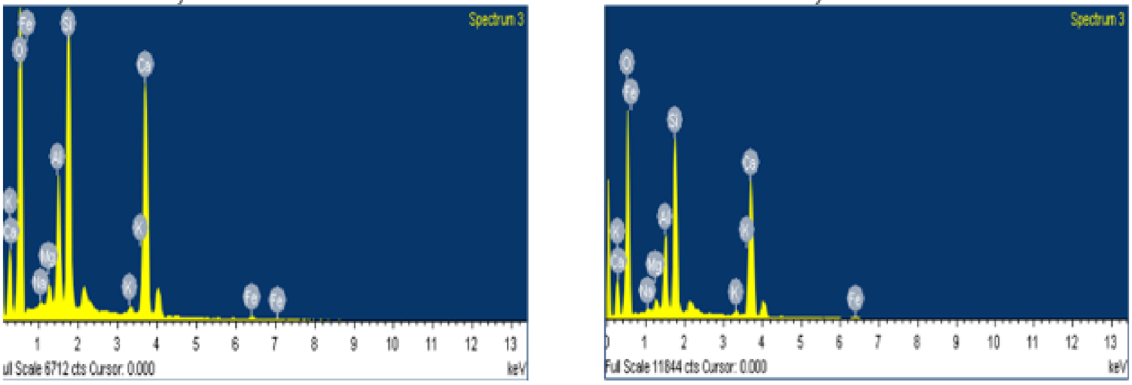
a) control mix

b) 3 % PW



c) 10 % GGBFS

d) 5 % MS



e) 3 % PW+ 10 % GGBFS

f) 3 % PW+ 5 % MS

Figure 8. EDS of optimised mix proportions of cement mortar

3.5 Environmental assessment

Environmental assessments of the different mortar mixes containing various industrial wastes evaluated energy consumption and carbon emissions. The values of EE and ECO_2 for the different mortar mixes are shown in Figures 9 and 10, respectively. The variations in the EE and ECO_2 of the various mixes with reference to the control mix are shown in Figures 9 and 10.

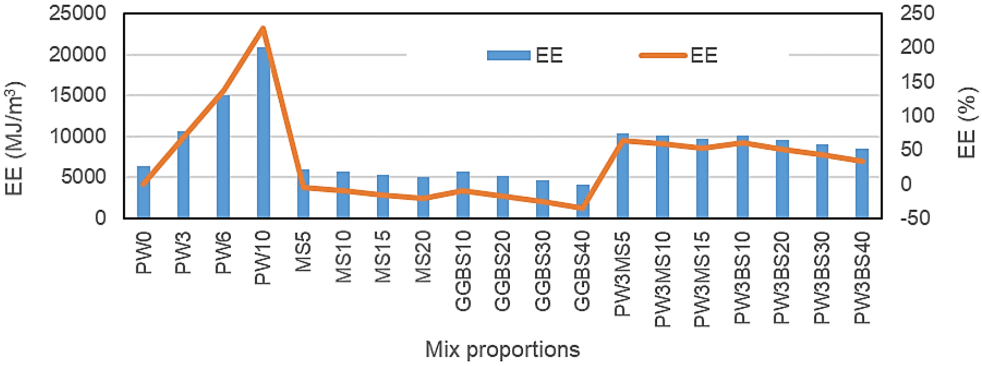


Figure 9. Energy consumption of different waste materials in mortar production

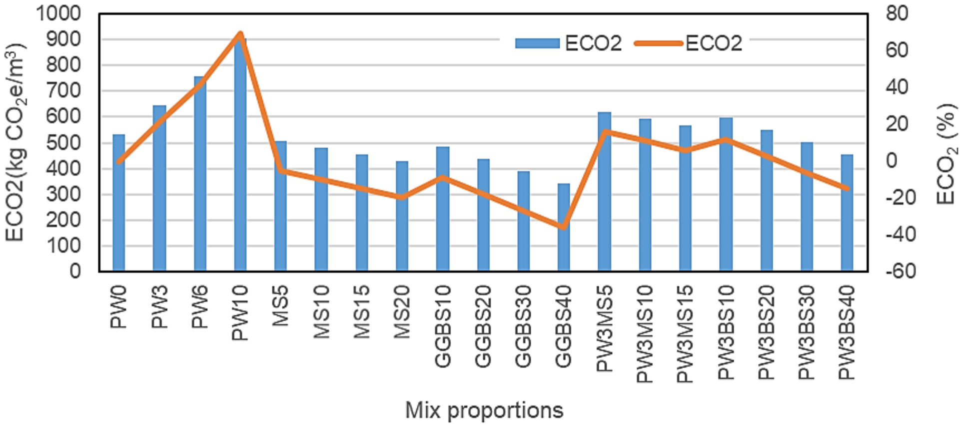


Figure 10. Variation of carbon emission of different mortar mixes

It was found that the incorporation of MS and GGBFS reduced the EE and ECO_2 compared with the control mix because of the lower consumption of energy and carbon emissions from the processing of these industrial by-products.

The use of PW in cement mortar provides significant economic and environmental benefits. This innovative solution addresses refuse-management issues while simultaneously promoting the sustainability of building materials. The economic and ecological repercussions of incorporating PW into cement mortar with or without industrial waste were the focus of this analysis. The incorporation of PW into concrete has the potential to reduce costs in numerous construction sectors. PW, which is inexpensive or even free, can be utilised as an additional material to reduce the cost of conventional cement mortar components. The use of PW in concrete potentially reduces the need for conventional raw materials such as aggregates. This aids in the preservation of natural resources and mitigates the economic repercussions of fluctuating material costs. Occasionally, municipalities and waste management agencies incur substantial expenses associated with the collection, classification, and disposal of plastic refuse. The emergence of novel opportunities for research, innovation, and development has been facilitated by advancements in technology and methodologies for incorporating PW into cement mortar. This could lead to the growth of companies specialising in the production of environmentally friendly construction materials, thereby fostering economic advancement and employment opportunities in these sectors. The competitiveness of construction enterprises may be enhanced by incorporating PW into cement mortar, as sustainability becomes an essential component of building operations.

3.6 Performance evaluation

The performance indices of the different mortar mixes were evaluated with reference to the control mix in terms of strength and environmental assessment, as shown in Figures 12 and 13. If the performance of the different mix proportions in terms of strength was less than 1, the performance of that mix was inferior to that of the control mix, and a value greater than 1 indicated a superior performance of the mix. In the case of environmental assessment, a value of less than 1 is considered more environmentally friendly, and a higher value is considered less eco-friendly. The PW (3 %), MS (10 %), and GGBFS (20 %) had superior strength performance compared with the control mix, as the value of the performance was evaluated to be more than 1, as illustrated in Figure 12. Mix PW10 had the lowest performance among all the mix properties, owing to having the lowest compressive strength among all the mixes. The performance index indicates the desired performance of any mix, that is, superior or inferior with respect to the control mix in various aspects such as strength, durability, and ecological impact.

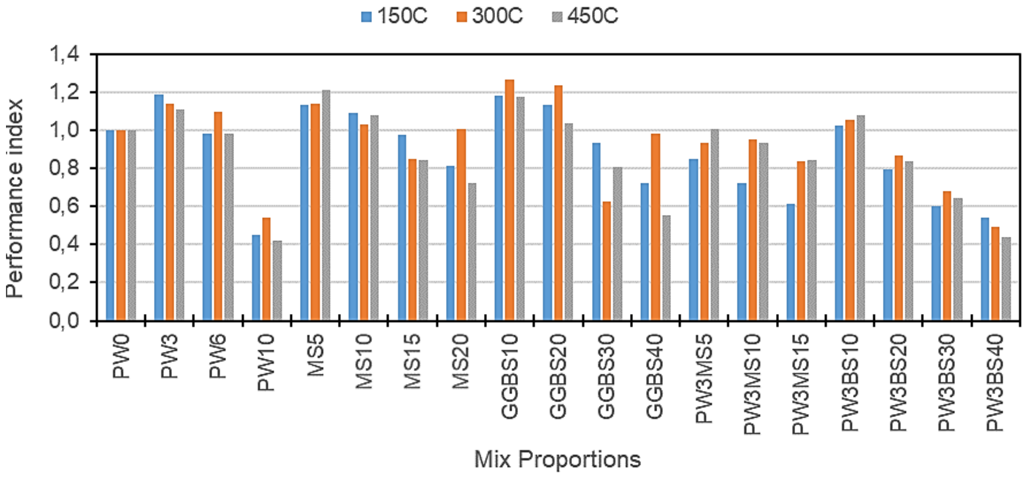


Figure 11. Performance evaluation of different mortar mixes in term of strength

The performance indices of the different mortar mix proportions in terms of energy consumption and carbon emissions are illustrated in Figure 12.

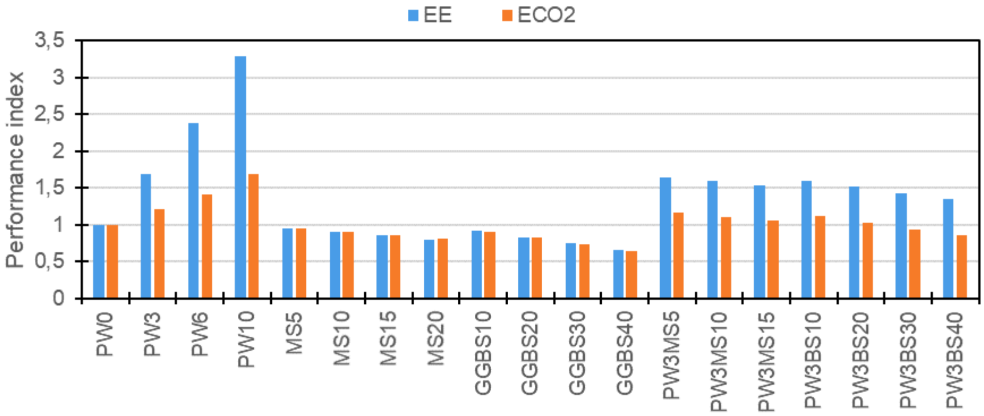


Figure 12. Performance evaluation of the different mix proportions

In this case, the lowest values of these parameters are considered the best because the motive of this research is to produce end products that produce lower carbon emissions and consume less energy. The incorporation of MS and GGBFS produced sustainable end products, as the value of the performance index was less than one compared with that of the control mix. However, the addition of PW to the mortar consumed more energy and produced more carbon emissions than the control mix. The performance index of any parameter in the mortar mixes indicates the optimum mix for the desired outcome. This provided a benchmark for quality control.

4 Conclusions

In this study, the effects of elevated temperatures on the mass and compressive strength of mortar were studied experimentally. The environmental impact assessment of different mortar mixes containing plastic and industrial wastes through sand and cement substitution were investigated. The following observations were made in this study:

- The colour of the specimens changed with increasing temperature owing to the evaporation of moisture and degradation of the materials. PW in the mortar began to soften, resulting in slight deformation and the formation of micro voids within the matrix.
- The weights of specimens with different mix proportions decreased with increasing temperature. The evaporation of water caused the mass loss to increase with higher temperatures, irrespective of the presence of industrial residues.
- Maximum mass loss was observed in the mortar mix containing PW. The maximum mass losses were 7, 9 and 15 % at 150, 300 and 450 °C, respectively.
- The enhancement of residual compressive strength of the various mortar mixtures was at 300 °C. This is may be due to narrow configuration of the cement matrix consisting of supplementary cementitious materials in mortar specimens as a result of water evaporation. At 450 °C, a decrease in strength of the mortar may be attributed to the dehydration of the cement paste and the decomposition of the matrix, as well as the presence of voids due to degradation of material or decomposition of C-S-H.
- The laboratory results were validated by microstructural analyses using SEM and EDS. The micrographs and elemental compositions of the selected mix proportions confirmed the macro strength of the mortar mixes.
- Mortar mixes containing industrial waste reduce environmental impact. The energy consumption, and carbon emissions of the different mix proportions containing various industrial by-products were lower than those of the control mix.
- Industrial wastes, such as PW, MS, and GGBFS, up to 6, 5, and 10 %, respectively, can be effectively used in mortar mixes.
- The utilisation of these industrial wastes produces sustainable end products and are an efficient approach for sustainable construction.

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