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Research Article

Compressive strength and fire resistance of mortar containing spent garnet as partial sand replacement

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ABSTRACT

The increasing demand for sand in construction, driven by rapid urbanization, has led to unsustainable sand mining and significant environmental degradation. This study addresses the urgent need for sustainable alternatives by investigating the use of spent garnet, a waste by-product from abrasive blasting, as a partial replacement for fine aggregate in mortar. Despite its widespread disposal in landfills, spent garnet has potential as a viable substitute due to its high bulk density and angular particle structure. This research explores the effects of substituting sand with spent garnet at 10%, 20%, 30%, and 40% replacement levels. The novelty of this study lies in its integrated evaluation of workability, mechanical strength, and thermal resistance of mortar incorporating spent garnet. Results from flow table tests showed a progressive increase in flowability, with the 40% garnet mix achieving a maximum flow of 142%, compared to 68.3% for the control mix. Density increased from 4958 kg/m^3 (0% garnet) to 5180 kg/m^3 (40% garnet), enhancing packing efficiency. The highest compressive strength was recorded in the 20% replacement mix, with values of 37.95 MPa at 7 days and 50.99 MPa at 28 days, an increase of 12.5% and 42.3%, respectively, over the control mix. Thermal analysis revealed the lowest mass loss in 10% and 20% replacement mixes, with the 20% mix also showing improved fire resistance. These findings indicate that a 20% spent garnet replacement offers the optimal balance between workability, mechanical performance, and thermal stability. This approach not only enhances mortar properties but also promotes sustainable waste management and reduces reliance on natural river sand.

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1. Introduction

Construction has been one of the key industrial sectors driving economic growth and development in every country (Alaluo et al. 2021). While concrete is widely recognized as a fundamental building material, mortar–produced by blending cement, sand, and water also serves as a key component in building and infrastructure projects. As an adhesive substance, it fills gaps between units and is frequently used for plastering and joining building blocks. The increasing use of mortar in construction projects has led to higher consumption of river sand. According to Shitima and Suykens (2023), the rapid growth of urbanization has significantly increased the demand for sand. Allied Market Research reports that the construction aggregates industry, valued at $375.3 billion in 2021, is projected to grow to $621.1 billion by 2031, with a CAGR of 5.05% from 2022 to 2031

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(Digvijay and Onkar 2022). Sand, a non-renewable resource, is the most mined material in the world due to its broad use in constructing roads, buildings, and infrastructure, as well as in industries such as glass manufacturing and nuclear energy (Whiting 2019; Ludacer 2018). Excessive sand mining, however, has caused significant environmental issues including riverbank erosion, freshwater contamination, damage to aquatic ecosystems, and riverbed alterations (Sherry and Philippe 2022; Dinh et al. 2022; Muellegger et al. 2013). To address these problems, it is important to consider alternative waste materials as substitutes for sand in construction.

One such material is spent garnet, an industrial by-product produced from abrasive blasting, water jet cutting, and water filtration processes. In industries such as ship maintenance and repair, spent garnet has limited reuse and is often discarded after a few cycles, resulting in substantial waste generation (Muttashar et al. 2018). This waste is typically sent to landfills, contributing to environmental pollution. The negative environmental impact of spent garnet disposal has been highlighted by researchers such as Mokhatar et al. (2022) and Jamaludin et al. (2022a). In support of sustainability, the use of processed spent garnet at suitable replacement levels has been shown to enhance the strength of concrete when used as a cement substitute (Jamaludin et al. 2024). Several studies have focused on using spent garnet as a sand replacement in concrete (Huseien et al. 2019; Muttashar et al. 2018; Muthusamy et al. 2022; Jaafar et al. 2024; Ruslan et al. 2024). However, limited studies have explored the application of spent garnet in mortar, especially in relation to its fire resistance and mechanical performance compared to its role in concrete.

This study investigates the performance of mortar blended with processed spent garnet as a sand replacement. The aim is to assess its suitability and effectiveness in promoting sustainable construction while reducing landfill waste and conserving natural sand. This research addresses the gap in existing studies, which have primarily focused on concrete, by emphasizing mortar-specific properties and behavior.

2. Methodology

This study used ordinary portland cement, river sand, spent garnet, and tap water to produce mortar samples. Spent garnet was collected from a sandblasting industry in West Malaysia, then oven-dried and sieved to remove debris. Six mortar mixes were prepared: one control mix (100% river sand) and five mixes with 10–40% spent garnet replacing sand. Materials were mixed in a clean tray, cast into greased cube molds in layers, compacted, and left to set overnight. After demolding, specimens were cured in water for 7 and 28 days.

2.1. Materials

This study used cement, sand, spent garnet, and water as the primary materials. Ordinary portland cement was used as the sole binder. Tap water was utilized for preparation of the mortar mix and the curing process. The fine aggregate used is river sand with fineness modulus and water absorption is 3.94 and 3.12 respectively. The particle size distribution and microstructure of sand is illustrated in Figs. 1 and 2 correspondingly. Spent garnet was collected from the sandblasting-related industry in West Malaysia and transported by lorry to the laboratory. Upon arrival, the gunny bags full of spent garnet were placed in a closed container. At the laboratory, the spent garnet waste was placed in the oven and dried for 24 hours to ensure it was in an oven-dry condition. Then, it was sieved through a 600 µm sieve to remove debris. Fig. 3 illustrates the spent garnet: (a) as received, freshly/ raw material of spent garnet waste, and (b) after the drying and sieving process. The fineness modulus and water absorption of spent garnet is 2.91 and 6.18 respectively. The particle size distribution of spent garnet and SEM microstructure is illustrated in Figs. 4 and 5. The chemical composition of spent garnet is tabulated in Table 1.

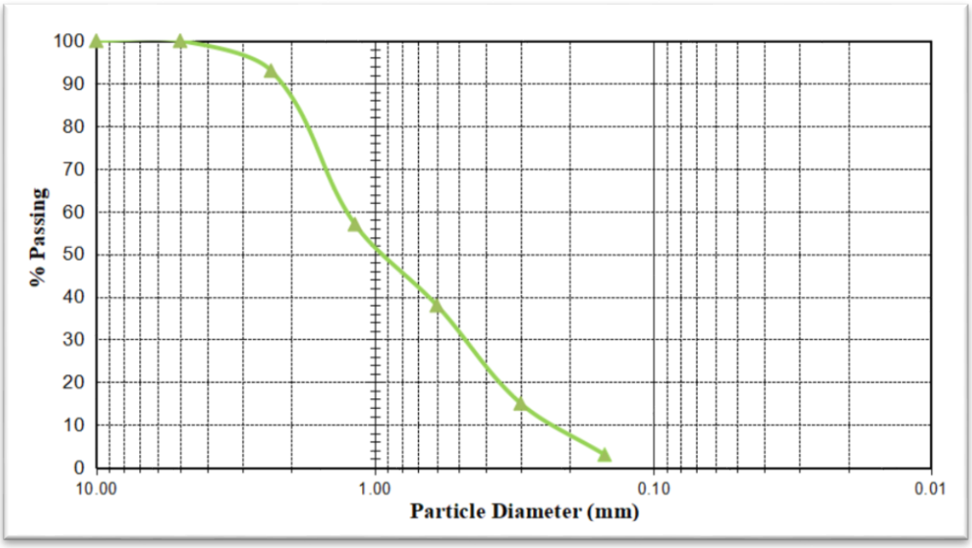

Fig. 1. Particle size distribution of sand.

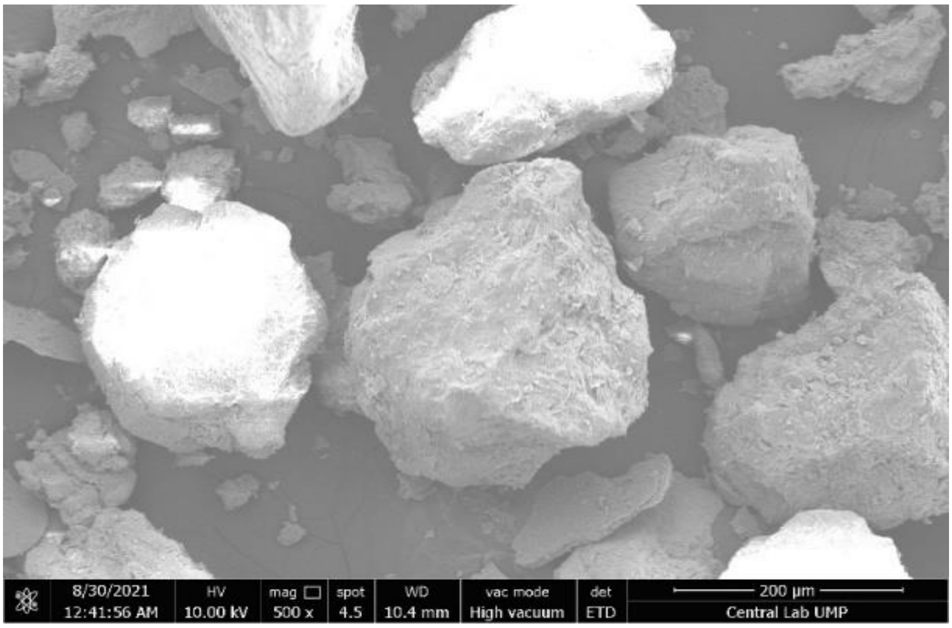

Fig. 2. Image of sand at magnification of 500x.

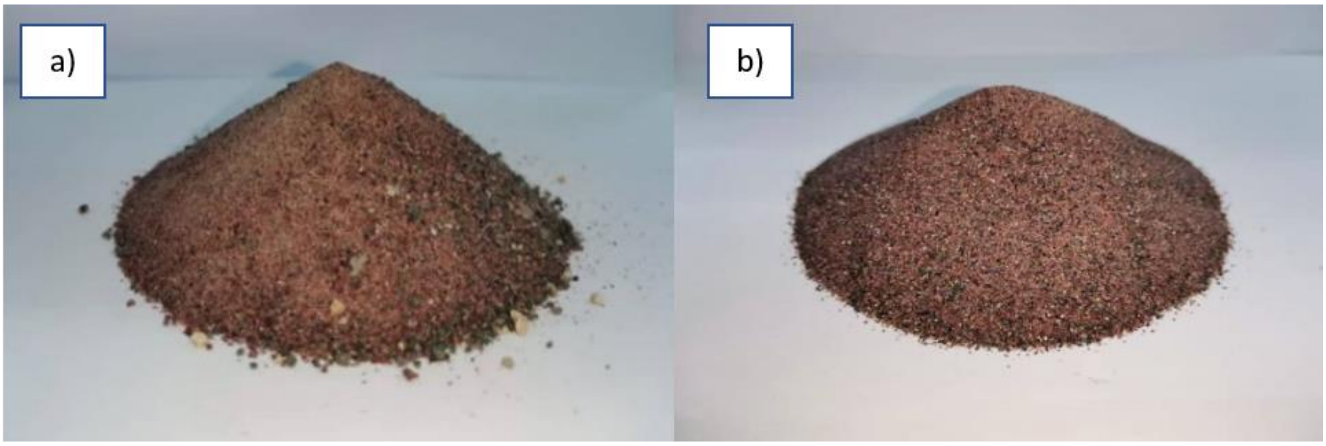

Fig. 3. Spent garnet: (a) As received, freshly/ raw material of spent garnet waste; (b) After the drying and sieving process.

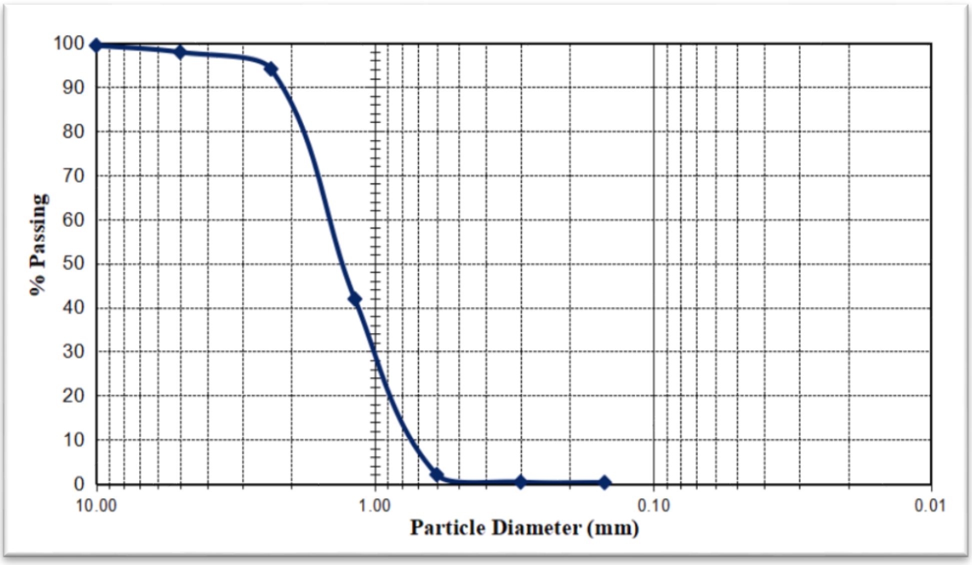

Fig. 4. Particle size distribution for spent garnet.

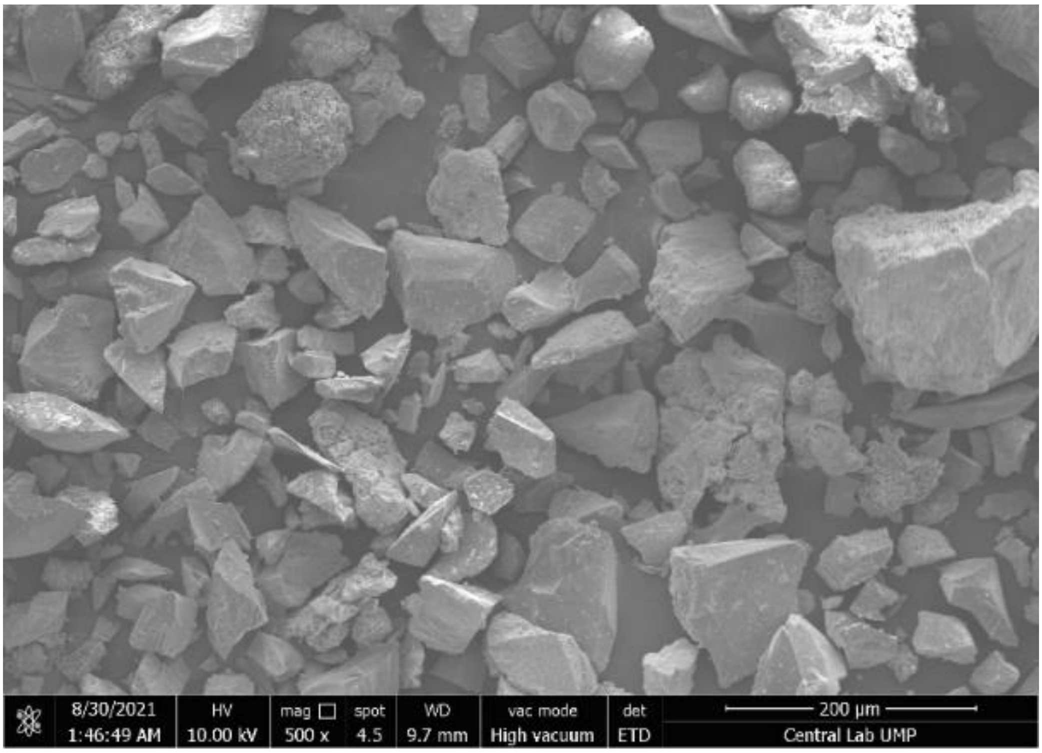

Fig. 5. Image of spent garnet at magnification of 500x.

Table 1. Chemical composition of spent garnet.

Chemical composition	Spent garnet (%)
Silicon dioxide (SiO^2)	39.04
Aluminium oxide (Al_2O_3)	13.40
Iron oxide (Fe_2O_3)	40.23
Magnesium oxide (MgO)	4.08
Sulfur trioxide (SO_3)	0.38
Potassium oxide (K_2O)	0.32
Manganese (II) oxide (MnO)	1.03
Titanium (IV) dioxide (TiO_2)	1.53

2.2. Mix proportion and specimen preparation

Six mortar mixes were utilized in the experimental work, which was conducted at the concrete laboratory. The mortar with 100% river sand acting as fine aggregate was used as the control specimen. The other mixtures contained various percentages of spent garnet: 10%, 20%, 30%, and 40%. The mixture design for this research is presented in Table 2. Before mortar casting, molds were ensured to be in good condition without any defects or cracks in the inner part of it to prevent leakage of mortar mixture during the casting process. Then, the chosen mold was prepared by removing any dirt or hardened mortar pieces from its surface. Subsequently, a thin coating of grease was applied to the interior surface of the mold. The cement, sand, spent garnet, and water were weighed carefully. All materials were placed in a clean tray, beginning with the mixing of the dry components: cement, followed by sand, spent garnet, and finally water. The materials were thoroughly mixed and cast into cube molds in layers. After placing the first layer, it was compacted on a vibrating table, and the process was repeated for the next two layers. The mold was then placed on a storage rack and left overnight for the hardening process. After 24 hours, all cubes were demolded and labelled clearly for easier identification. Finally, the cubes were immersed in a curing tank filled with tap water for 7 and 28 days. During the experimental work, the humidity of the environment is between 80%–84% with temperature 27 °C to 30 °C. Fig. 6 presents the mortar specimens preparation process.

2.3. Testing

Four tests were conducted in this research: the flow table test, compressive strength test, density test, and fire resistance test. The workability of the mortar was assessed by conducting a flow table test immediately after mixing. The testing were conducted by adhering to the procedure in ASTM C1437-07 (2007). The compressive strength test was conducted to determine the mortar's ability to withstand load per unit area. The test was conducted using a compression testing machine on specimens that had undergone water curing for 7 and 28 days. Testing was conducted in accordance to ASTM C109M-20 (2020). The fire resistance test was carried out on 28 days water cured specimens. This test was performed to assess the performance of mortar with spent garnet as a partial replacement for fine aggregate under high temperatures. The specimens were exposed to temperatures of 200 °C, 400 °C, 600 °C, and 800 °C for two hours following the experimental method of past researcher Arioz (2007). Main apparatus used for the testing in this research work are illustrated in Fig. 7.

Table 2. Mix proportion (kg/m³).

Mix	Cement (kg/m³)	River Sand (kg/m³)	Sieved spent garnet (kg/m³)	Water content (kg/m³)
A (0%)	260	600	0	160
B (10%)	260	540	60	160
C (20%)	260	480	120	160
D (30%)	260	420	180	160
E (40%)	260	360	240	160

Fig. 6. Mortar specimen preparation process.

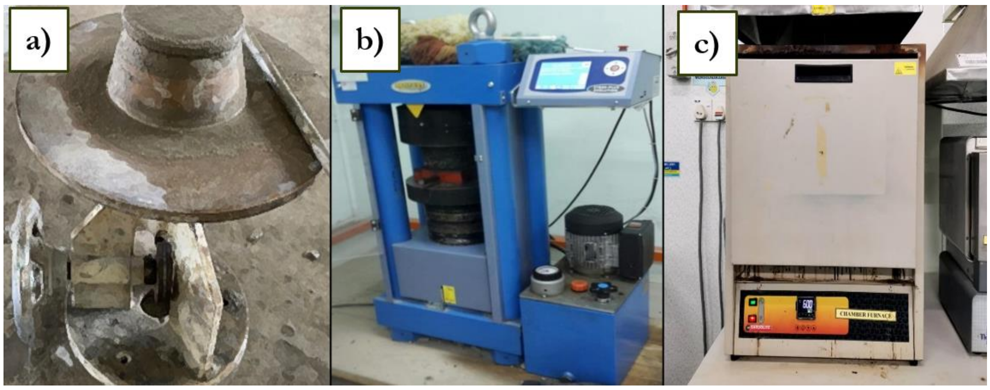

Fig. 7. Testing apparatus used: (a) Flow table; (b) Compression machine; (c) Electric furnace.

3. Results and Discussion

3.1. Flowability

Fig. 8 demonstrates the impact of varying percentages of spent garnet used as a partial replacement for fine aggregate on the flowability of the mortar. The results show an increase in mortar flow as the percentage of spent garnet replacement increases. The flow percentages for mortar with 0%, 10%, 20%, 30%, and 40% spent garnet are 68.3%, 92%, 101%, 127.3%, and 142%, respectively. The mortar with 0% spent garnet exhibits the lowest flowability, whereas mix with 40% spent garnet replacement exhibits the highest flowability. Fig. 9 illustrates the variation in the flowability of mix with 0% spent garnet and 40% spent garnet. The increment in the flowability in the mixture consisting higher content of spent garnet is attributed to its higher bulk density (2,740 kg/m³) in comparison to sand (1,935 kg/m³). Similar trend in workability improvement upon blending of spent garnet as a replacement for sand in concrete has also been reported by Budiea et al. (2021) and Jamaludin et al. (2022b). However, excessive replacement levels may lead to a segregation risk, potentially affecting cohesion and uniformity in fresh mortar. While increased flowability is advantageous for workability and ease of placement, its impact on hardened properties, particularly compressive strength, must be carefully assessed.

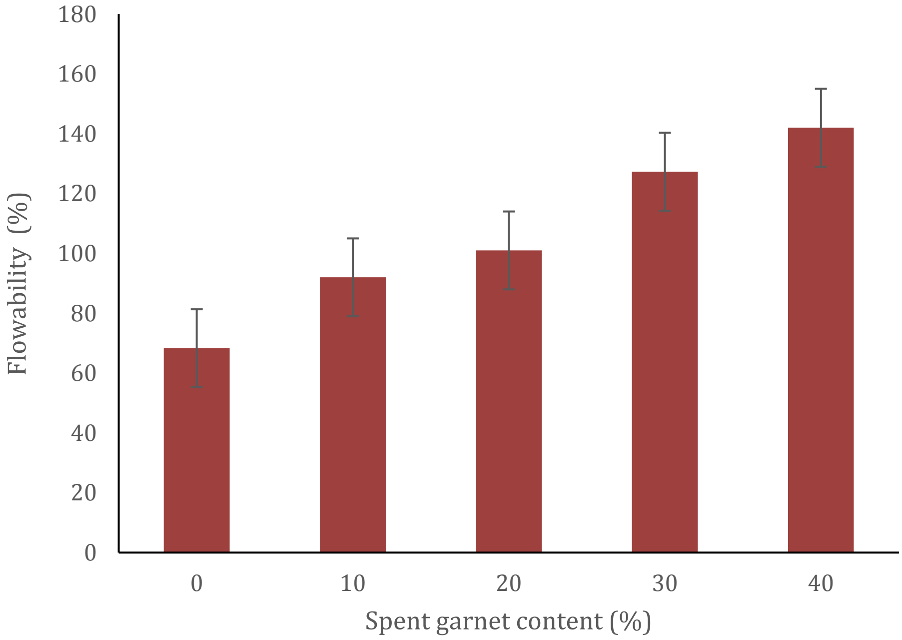

Fig. 8. Flowability test result.

Fig. 9. Flow of control mix and mortar with 40% spent garnet.

3.2. Density

The chart in Fig. 10 illustrates the effect of partially replacing fine aggregate with spent garnet on mortar density. Results indicate a consistent increase in density with higher replacement levels. Mortar incorporating 0%, 10%, 20%, 30%, and 40% spent garnet showed density values of 4,958 kg/m^3, 5,024 kg/m^3, 5,028 kg/m^3, 5,066 kg/m^3, and 5,180 kg/m^3, respectively. The 40% replacement mix exhibited the highest density, attributed to the higher bulk density of spent garnet (2,740 kg/m^3) compared to river sand, as well as its pore-filling effect, which enhances matrix compaction. Higher mortar density is generally linked to improved durability, reduced permeability, and increased resistance to environmental degradation, as supported by previous studies (Neville 2011; Li et al. 2019). Therefore, while 40% replacement yields the greatest density gain, practical applications should consider an optimal balance between increased density and mechanical or workability performance.

3.3. Compressive strength

Table 3 and Fig. 11 illustrate the compressive strength of mortar incorporating varying percentages of spent garnet as a partial replacement for fine aggregate. In general, all mixes, whether containing spent garnet or not–show increased strength over time due to continued C-S-H gel formation from uninterrupted hydration. The control mix (0% garnet) recorded the lowest strength, rising from 33.73 MPa at 7 days to 35.82 MPa at 28 days. The mix with 20% replacement achieved the highest strength at both ages, reaching 37.95 MPa and 50.99 MPa, respectively. This enhancement is likely due to finer size of spent garnet that acts as filler material contributing towards more compact internal structure of mortar mix. Other than that, the rough, angular texture of spent garnet could also be one of the factor that contribute towards improvement of bonding at the cement–aggregate interface. Replacements up to 40% also demonstrated strength gains over the control, possibly influenced by the higher density of the garnet particles.

However, higher replacement levels may introduce workability issues or reduced long-term durability, which should be considered in future applications. Similar findings have been reported in high-strength lightweight concrete by Muthusamy et al. (2022) and Jaafar et al. (2024).

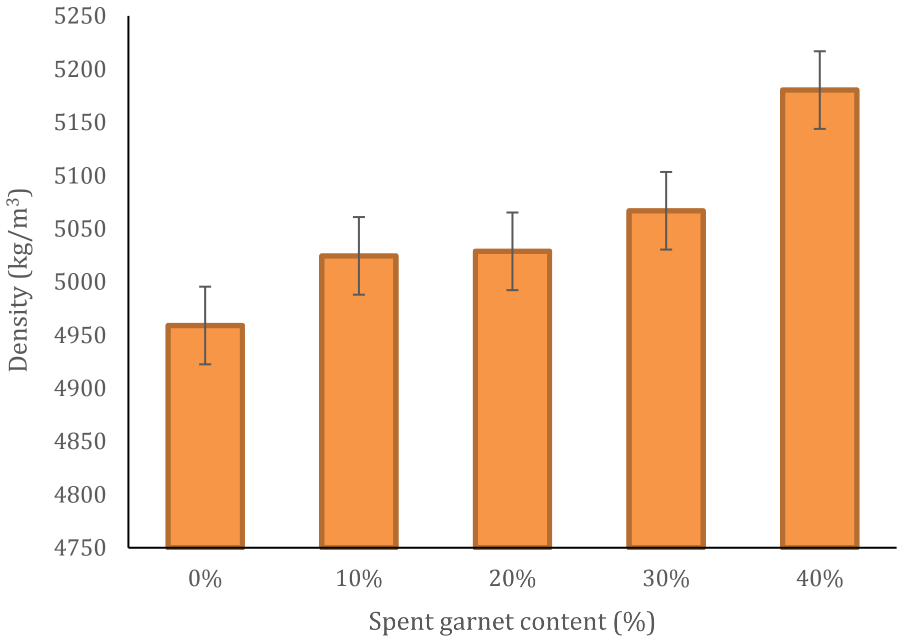

Fig. 10. Effect of spent garnet content on the density of mortar.

Table 3. Compressive strength of mortar with varying percentages of spent garnet.

Spent garnet content	Compressive strength (MPa) 7 days	Compressive strength (MPa) 28 days
0%	33.73	35.18
10%	36.97	40.90
20%	37.95	50.99
30%	33.15	49.65
40%	31.83	41.51

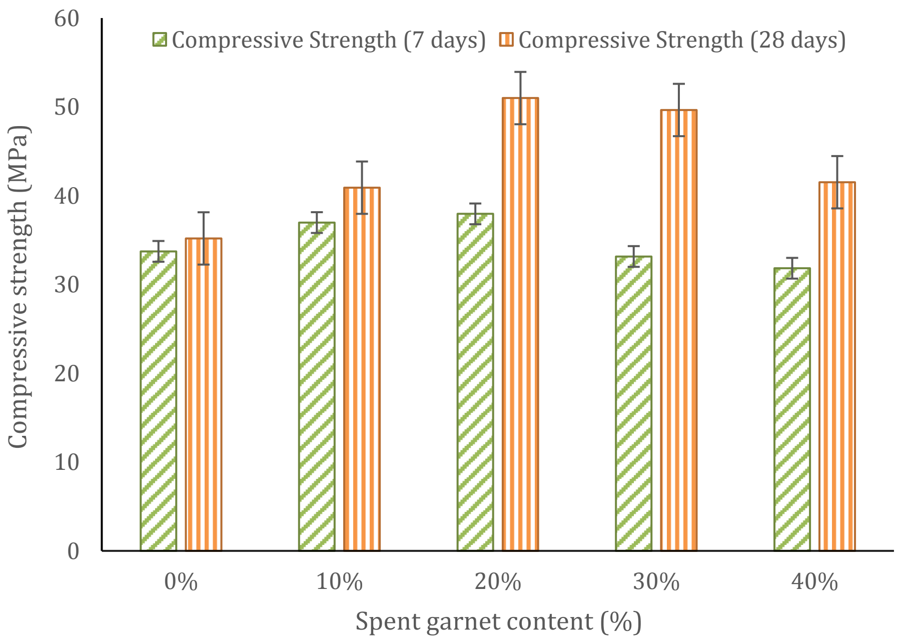

Fig. 11. Effect of spent garnet on compressive strength of mortar.

3.4. Fire resistance

Table 4 and Fig. 12 illustrate the percentage of mass loss in mortar when using different proportions of spent garnet. The chart indicates that the percentage of spent garnet replacement as sand is directly proportional to the mass loss of the mortar.

The mass loss for mortar with 10% spent garnet replacement at 200 °C, 400 °C, 600 °C, and 800 °C was 8.87%, 12.1%, 13.18%, and 14.12%, respectively. The mortar with 40% spent garnet exhibited the highest mass loss at 400 °C and 800 °C, with values of 12.23% and 14.33%, respectively. As expected, mass loss increased with rising temperatures. Similar observations have been noted by previous researchers, Nayel et al. (2020) and Jaafar et al. (2024). Among the different replacement levels, mortar containing 10% and 20% spent garnet showed the least mass loss. This occurred because spent garnet helps fill pores, making the mortar denser. However, excessive garnet replacement can lead to increased mass loss, as it enlarges voids within the mortar specimen.

Table 4. Percentage of mass loss in mortar when using different proportions of spent garnet.

Spent garnet content	Mass loss (%) 200	Mass loss (%) 400	Mass loss (%) 600	Mass loss (%) 800
0%	9.36	12.22	13.47	13.94
10%	8.87	12.10	13.18	14.12
20%	9.04	11.99	13.61	14.03
30%	8.99	12.20	13.81	13.93
40%	9.35	12.23	13.30	14.33

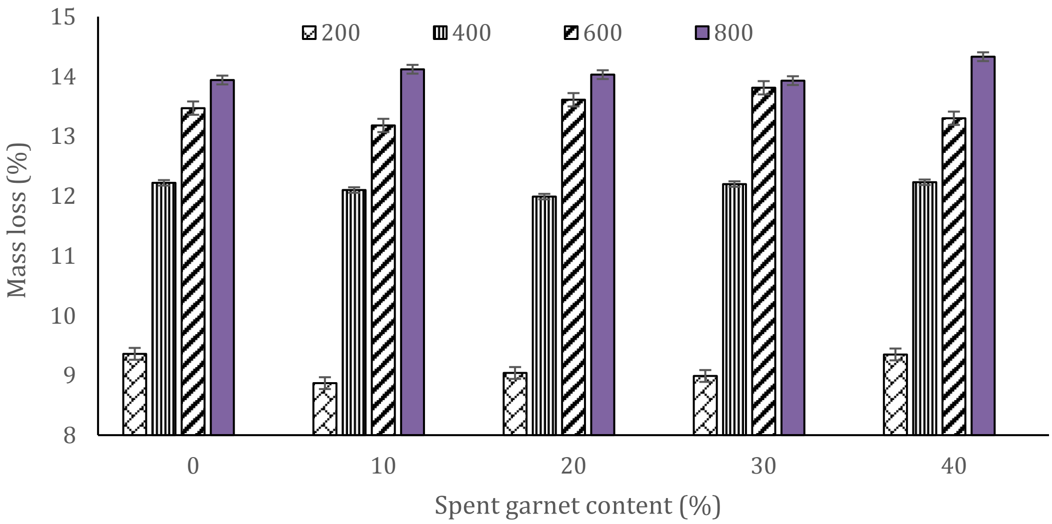

Fig. 12. Mass loss of mortar containing different spent garnet contents when subjected to diverse high temperatures.

4. Conclusion*s*

The study explores the effects of using spent garnet as a partial replacement for fine aggregate in mortar, examining flowability, density, compressive strength, and thermal resistance. Flowability increased with higher garnet content, from 68.3% at 0% replacement to 142% at 40%, due to the higher bulk density of garnet (2,740 kg/m^3) compared to sand (1,935 kg/m^3). The 40% replacement mix showed the greatest workability. However, excessive replacement could cause segregation, affecting the mixture's cohesion. Density also improved with increased garnet content, rising from 4,958 kg/m^3 at 0% replacement to 5,180 kg/m^3 at 40%. This is due to garnet's higher density and pore-filling properties, leading to better matrix packing and potentially greater durability.

Compressive strength increased across all mixes with curing time. The 20% spent garnet mix exhibited the highest compressive strength (37.95 MPa at 7 days and 50.99 MPa at 28 days), attributed to garnet's rough texture, which enhances bonding with cement. Although the control mix had the lowest strength, mortars with 0% and 10% garnet showed relatively high strength in comparison to other mixes. Thermal analysis showed that mass loss increased with temperature and garnet content. Mortars with 10% and 20% replacement exhibited the lowest mass loss, suggesting an optimal balance between garnet and cement, which improved thermal stability. In contrast, excessive garnet increased porosity, weakening the matrix under high heat. Based on the overall results, the optimum spent garnet replacement for enhanced mortar performance, balancing workability, strength, and thermal resistance, is 20%.

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Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Author Contributions

All of the authors made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; were involved in drafting the manuscript or revising it critically for important intellectual content; and gave final approval of the version to be published.

Data Availability

The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

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