SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Applied Mechanics

Journal homepage:
https://semarakilmu.com.my/journals/index.php/appl_mech/index
ISSN: 2289-7895

A Review on the Recycling of Spent Garnet as a Mixing Ingredient in Concrete

Sofia Adibah Jasni[1], Khairunisa Muthusamy[1,2,*], Mohd Faizal Md Jaafar[1], Shahrul Niza Mokhatar[3], Mohamed A. Ismail[4]

[1] Faculty of Civil Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Lebuh Persiaran Tun Khalil Yaakob, 26300, Gambang, Pahang, Malaysia
[2] Centre for Sustainability of Mineral and Resource Recovery Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Lebuh Persiaran Tun Khalil Yaakob, 26300, Gambang, Pahang, Malaysia
[3] Faculty of Civil Engineering and Built Environment, Universiti Tun Hussien Onn Malaysia, 86400 Parit Raja, Johor, Malaysia
[4] Department of Civil and Environmental Engineering, Brunel University London, London, UB8 3PH, United Kingdom

ARTICLE INFO

Article history:
Received 27 January 2025
Received in revised form 2 March 2025
Accepted 9 March 2025
Available online 30 March 2025

Keywords:
Spent garnet; sand replacement; concrete; properties; sustainability

ABSTRACT

Construction industry has increased rapidly leading to increase in concrete usage. This contributes to its limitation of natural resources and issue of sand shortage in certain place. This problem primarily due to the uncontrolled river sand mining. The demand for eco-friendly construction methods has driven research into substitute materials for conventional sand, and aggregates. Thus, embracing industrial by-products known as spent garnet as alternative materials presents an appealing solution to mitigate reliance on sand resources, thereby contributing to the sustainability of river ecosystems. Spent garnet is a waste derived from the surface treatment process in the shipping industry and is usually dumped in landfills. This review critically examines the viability of integrating spent garnet into construction materials. Comprehensive assessments of the physical and mechanical properties of these composite materials shed light on the potential improvements and challenges associated with the use of spent garnet. Ultimately, the review synthesizes the current state of knowledge on spent garnet in construction, offering valuable insights for researchers and industry professionals seeking innovative, sustainable solutions in materials science and waste management.

1. Introduction

In many nations around the world, concrete has been a top choice for construction materials. As more buildings are constructed, cement usage and other natural resources (fine aggregate, coarse aggregate) has increased the usage tremendously [1]. The unique advantages compared to other materials became the main reasons for concrete to be used in terms of its cost, mechanical features, and even its durability properties [2]. The escalating global demand for cement, a fundamental material in infrastructure development, has exacerbated environmental challenges, particularly

* *Corresponding author.*
E-mail address: khairunisa@umpsa.edu.my

https://doi.org/10.37934/aram.134.1.123141

through significant carbon dioxide (CO_2) [3]. According to Global Market Insights [4], the global construction aggregates market was valued at over $450 billion in 2022, and is expected to grow at a 6% Compound Annual Growth Rate (CAGR) from 2023-2032. In 2015, the construction sector consumed 48.3 billion metric tons of natural aggregates, however, by the end of 2024, global consumption of construction aggregates is expected to reach 62.9 billion metric tons [5]. The annual global use of almost 25 billion tonnes of concrete [4] and it continue increase resulting rising consumption of the natural resources such as sand and gravel. Continuous use of river sand and other natural resources will lead to the depletion of its sources [6]. Extensive mining of river sand poses an undesirable impact on the ecosystem and community as well. Utilizing alternative materials derived from other sources to play the role of sand in concrete production would be one of the solutions [6]. The option of discovering potential use of any waste material for concrete manufacturing would reduce high dependency on river sand supply and lessen waste thrown at landfills.

Garnet is a type of mineral utilized as gemstones and abrasives since the Bronze Age [7]. Garnets are mostly found with reddish shades but can be, orange, yellow, green, purple, brown, blue, black, pink, and colorless [8]. This material is often utilized in waterjet cutting [9]. It is regularly used in the industry owing to its better properties, availability, and affordability as compared to other abrasive materials [10]. Garnet is starting to substitute silica in abrasives because silica is unsafe for workers' health [11]. Garnet is the most used among other abrasive materials Globally, there are four countries that remain leading in garnet manufacturing [12]. These are India, China, Australia, and the United States. India leads the globe in production, with 700,000 metric tons of garnet [13]. According to Statista Research Department [14], the production volume of garnet (abrasive) from mines in India amounted to an estimated 7085 metric tons in the financial year 2023.

The increasingly used garnet in various industries contributes to the prosperity of the producing sector. At the same time, the generation of spent garnet which is disposed of as waste after it is well used for certain industrial activity consumes spaces at landfills and creates environmental concern. A waterjet cutter when aimed at a piece of metal, ceramic, or stone, cuts the material producing very little dust [8]. Before being disposed of as waste, garnets that have been utilized in the cutting and sandblasting industry would be recycled until cannot be used anymore [15]. Recycling of blasting waste is one of the alternatives adopted to reduce the quantity of waste to be thrown. Usage of garnets can be up to 3-5 times before they are disposed [16]. This waste known as spent garnet is only discarded after it is exhausted and becomes unsuitable to be used for abrasive blasting [16]. This solid waste is commonly dumped in landfills [17].

The practice of heaping spent garnet waste at the wasteyard would consume space on the land which could be used for better purposes. The global build-up of wasted garnet is dangerous to the environment because it may contaminate streams when it gets into them from runoff or flooding [16]. The undesirable impact on the environment due to spent garnet dumping has also been pointed out by past researcher [18]. Thus, reutilizing these materials reduce environmental degradation and promotes saving of resources [19]. However, the selection of the finest management system is influenced mainly on cost and on local environmental standards [20]. Success in recycling this waste in production of concrete would reduce the waste disposed, lower the waste management cost faced by the industry and contribute towards cleaner surrounding. This paper presents a review on the utilization of spent garnet as constituent in cement based composite material.

2. Methodology
2.1 Physical Properties

Garnet in Figure 1(a) is a sand-like particle with having unalike color from natural sand. This mineral sand falls in the group of ore deposits [21]. Brilliant bright red colors and transparency make attractive semiprecious gemstones and inferior quality as abrasive, steel cutting, leather and wood polishing, and water filtration media [7]. Spent garnet as illustrated in Figure 1(b) has a reddish color. In terms of physical appearance, spent garnet possesses a shape almost comparable to sand as highlighted by Jaafar *et al.,* [22] in Figure 2. Spent garnet particles are typically angular in shape than the irregular form of sand particles. Table 1 tabulates the physical properties of spent garnet which does not differ much from one sample to another. The specific gravity of spent garnet obtained from different sources is between 2.9 to 4.1.

(a) (b)

Fig. 1. Comparison between (a) Garnet (b) Spent garnet

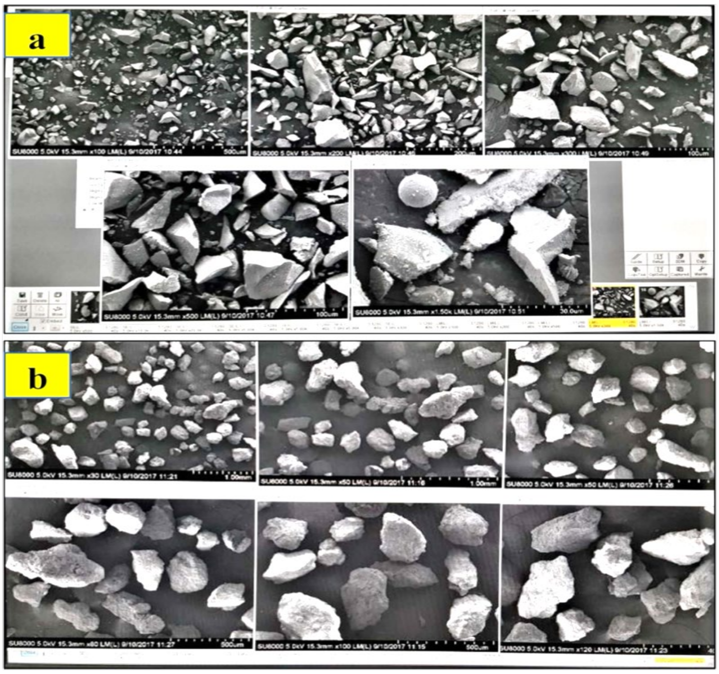

Fig. 2. FESEM microstructure (a) Spent garnet (b) Sand [22]

Generally, the bulk density ranges from 1800 kg/m³ to 2300 kg/m³. The hardness of this material is between 7.5 to 8.0. The diverse application methods in the industry cause slight variations in the physical properties of spent garnet [23]. Due to the physical characteristics of spent garnet particles, it can improve the interlocking and mechanical bonding between the aggregate and the cement paste. Thus, the strength of the concrete was enhanced by the addition of spent garnet. The particle size of spent garnet often has a narrower particle size distribution compared to natural sand as presented in Figure 3 [24]. Spent garnet particles which is finer than natural sand can produce a denser concrete matrix, contributing to the development of strength.

Table 1
Physical properties of spent garnet

Reference	Specific gravity	Fineness modulus	Hardness	Bulk density (kg/m^3)	Water absorption (%)	pH value
[16]	3.0	2.05	7.5	1922	6	-
[22]	2.9	-	7.5 to 8.0	2300	6	8.3
[25]	2.9	-	7.5 to 8.0	-	6	7
[26]	1.97	1.97	7.5 to 8.0	-	-	-
[24]	-	-	-	2300	5.8	-
[27]	-	-	-	1804	5.5	-
[28]	3.8	-	-	-	10.2	-
[29]	3.75	1.68	-	-	6.12	-
[30]	-	2.07	-	2121	-	-
[31]	4.1	1.75	-	-	1.4	-

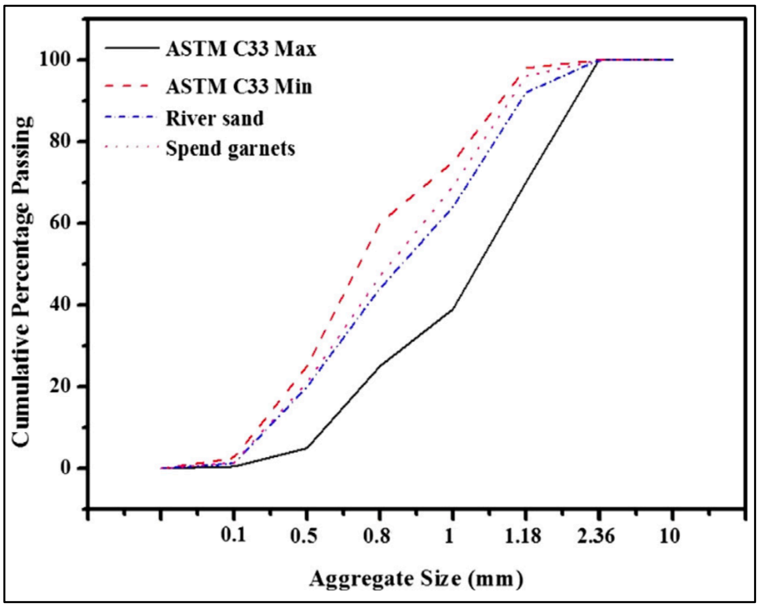

Fig. 3. Particle size distribution of spent garnet [24]

2.2 Chemical Properties

Based on Table 2, spent garnet has the highest composition of Ferric Oxide (Fe_2O_3) where it ranges from 33.10 to 43.40 followed by Silicon Dioxide (SiO_2) which ranges between 28.30 and 36.00. The reddish color of the spent garnet is mainly due to the highest composition of iron oxide. The presence of copper, zinc, and lead definitely will interrupt the hydration reaction of concrete and its mechanical properties [32]. The presence of heavy metal would probably help the hydration [33] as well. According to Muttashar *et al.,* [21], the leaching test shows that the heavy metal content inside the spent garnet is lesser than the control limits where the Toxicity Characteristic Leaching Procedure (TCLP) analysis established by the US EPA.

Table 2
Oxide composition of spent garnet

	[34]	[22]	[25]	[24]	[35]	[36]	[29]	[37]	[31]	[38]
Fe_2O_3	3.21	43.06	43.06	43.10	33.10	43.40	40.23	42.68	39.7	44.97
SiO_2	40.37	33.76	33.76	33.70	36.00	28.30	39.04	34.12	29.2	27.13
Al_2O_3	17.95	13.88	13.88	13.90	17.70	14.30	13.40	13.75	17.5	17.73
CaO	34.63	4.15	4.15	4.15	5.48	4.45	-	3.98	2.47	1.89
MgO	2.09	2.91	2.91	2.91	5.97	4.68	4.08	2.85	3.22	4.90
K_2O	0.05	0.14	0.14	-*	0.10	0.04	0.32	0.11	-	0.01
MnO	0.18	1.08	-	-*	0.63	1.01	1.03	-	1.12	-
TiO_2	0.31	0.78	-	0.78	0.42	1.67	1.53	-	-	-
P_2O_5	0.02	0.21	-	-*	0.10	-*	-	-	-	0.41
ZnO	-	0.06	-	-*	0.04	0.05	-	-	0.26	-
Cr_2O_3	-	0.05	-	-*	0.06	0.11	-	-	-	-
Na_2O	0.08	-*	-	-*	0.20	-*	-	-	-	-
V_2O_5	-	-*	-	-*	0.04	-*	-	-	-	-
SO_3	-	-*	-	-*	0.02	0.03	0.38	-	-	0.06

3. Fresh Properties

The use of spent garnet as a replacement for partial fine aggregate influences the fresh properties of cement-based composites as presented in Table 3. Figures 4 and 5 illustrates the increase in flowability of mortar upon integration of spent garnet. Upon blending the spent garnet partially replacing the natural sand, the fresh mix become increasingly workable. According to Huseien *et al.*, [23], the integration of spent garnet ranging from 25% and more to total sand replacement increases mortar workability. This is due to the higher bulk density value of spent garnets compared to river sand. This contributed to a reduction in spend garnet's volume in the AAMs mixture and minimized directly the water adsorption. Researchers elsewhere Mehta and Paulo [39], highlighted that the flow ability of mortar containing 25%, 50%, 75%, and 100% of spent garnet as fine aggregate replacement, increases as larger content of spent garnet is used. Usage of the spent garnet with higher density causes the mortar to spread wider and result in higher flow ability. A similar pattern has been observed regarding rising slump value when spent garnet is incorporated as fine aggregate replacement in concrete.

Table 3
Workability of cement-based composites containing spent garnet

References	% of spent garnet	Size of spent garnet	Concrete type	Workability	Type of testing
[22]	0, 25, 50, 75, 100	Passing 2.35 mm, retained 212 µm	Self-compacting geopolymer concrete	Increased	Slump flow test, T50 slump flow test, L-box test, V-funnel test
[24]	0, 25, 50, 75, 100	-	Alkali-activated mortars	Increased	Flow table test
[39]	0, 25, 50, 75, 100	Sieved through 5 mm	Mortar	Increased	Flow table test
[30]	0, 10, 20, 30, 40	Passing 2.36 mm	High-strength lightweight aggregate concrete	Increased	Slump test
[29]	0, 10, 20, 30, 40	Passing 2.36 mm	lightweight aggregate concrete	Increased	Slump test
[31]	0, 10, 20, 30	Sieved through 1.18 mm	Concrete	Increased	Slump test

Besides, the concrete mixture becomes more workable when a larger content of spent garnet is used. A similar trend of improved workability was observed in other types of concrete blended with spent garnet namely self-compacting geopolymer concrete [36], lightweight aggregate concrete [30] and plain concrete [31]. The properties of spent garnet which possesses higher density than sand cause a lesser volume of it to replace the sand when partial fine aggregate in the concrete mix is done by the weight of sand. This causes extra water to be available due to a lesser quantity of spent garnet resulting in less water being required to cover the surface area. The variation in the physical characteristics of spent garnet to sand causes changes in the fresh properties of concrete or mortar. According to Goncalves *et al.,* [38] the particle size distribution, profile, and texture of fine aggregate have an apparent effect on fresh properties of mortar. A similar observation has been noted by Morizki and Imam [40] in concrete due to the shape, surface morphology, and particle size distribution of the fine aggregate used.

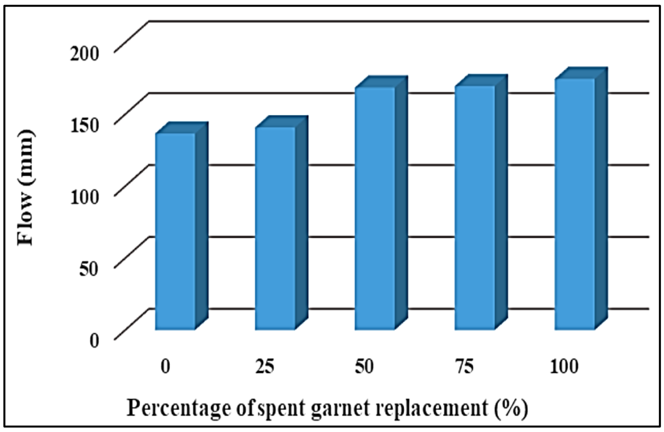

Fig. 4. Flowability result of mortar [39]

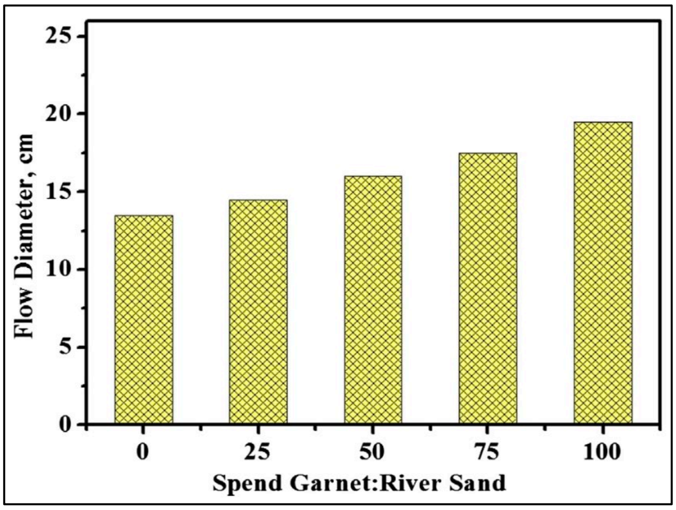

Fig. 5. Flow diameter with diverse content of spent garnets [24]

4. Mechanical Properties

A good quality concrete for construction applications is determined based on its workability, strength and durability. Table 4 tabulates the mechanical properties of the mortar and concrete when blended with spent garnet as sand replacement. Most findings reported positive contribution of spent garnet use as sand replacement in enhancing the hardened construction material strength.

Table 4
Mechanical properties

References	% of spent garnet	Types of mortar and concrete	Mechanical properties		
			Compressive Strength	Flexural Strength	Splitting Tensile Strength
[41]	0, 11.25, 12.5, 13.75, 15	Concrete	Increased at 12.5%.	-	-
[22]	0, 25, 50, 75, 100	Self-compacting geopolymer concrete	Decreased for all replacements.	Decreased for all replacements.	Decreased for all replacements.
[24]	0, 25, 50, 75, 100	Alkali-activated mortars	Increased at 25% of replacement.	Increased at 25% of replacement.	Increased at 25% of replacement.
[42]	0, 20, 40, 60, 80, 100	High strength concrete	Increased at 40% of replacement.	Increased at 40% of replacement.	Increased at 40% of replacement.
[17]	0, 10, 20, 30, 40	Concrete	Increased at 20% of replacement.	-	-
[39]	0, 25, 50, 75, 100	Mortar	Increased at 50% of replacement.	-	-
[29]	0, 10, 20, 30, 40	Lightweight, aggregate, concrete	Increased at 20% of replacement.	Increased at 20% of replacement	Increased at 20% of replacement
[30]	0, 10, 20, 30, 40	High strength, lightweight, aggregate, concrete	Increased at 20% of replacement.	-	-
[31]	10, 20, 30	Concrete	Increased at 10% of replacement.	-	Increased at 20% of replacement

4.1 Compressive Strength

Generally, all specimens blended with spent garnet as sand replacement exhibit strength increment as curing age increases. Figure 6 illustrates the compressive strength of concrete containing spent garnet as sand replacement continue to increase as curing age become longer. Most study findings indicate that adding a suitable quantity of waste garnet 25 % of the volume boosts the concrete strength. According to Huseien *et al.,* [23], 25% garnet to river sand substituted for the sand provide the best hardened alkali-activated mortars strengths and improved pore structure. Similarly, Muttashar *et al.,* [21], reported that the best results for self-compacting concrete were obtained in terms of workability and mechanical characteristics at a 25% garnet substitution level. When garnet content was raised over 25%, self-compacting concretes underwent strength declination. Jamaludin *et al.,* [28], revealed that enhanced strength performing lightweight aggregate concrete was able to be produced by integrating 20% spent garnet.

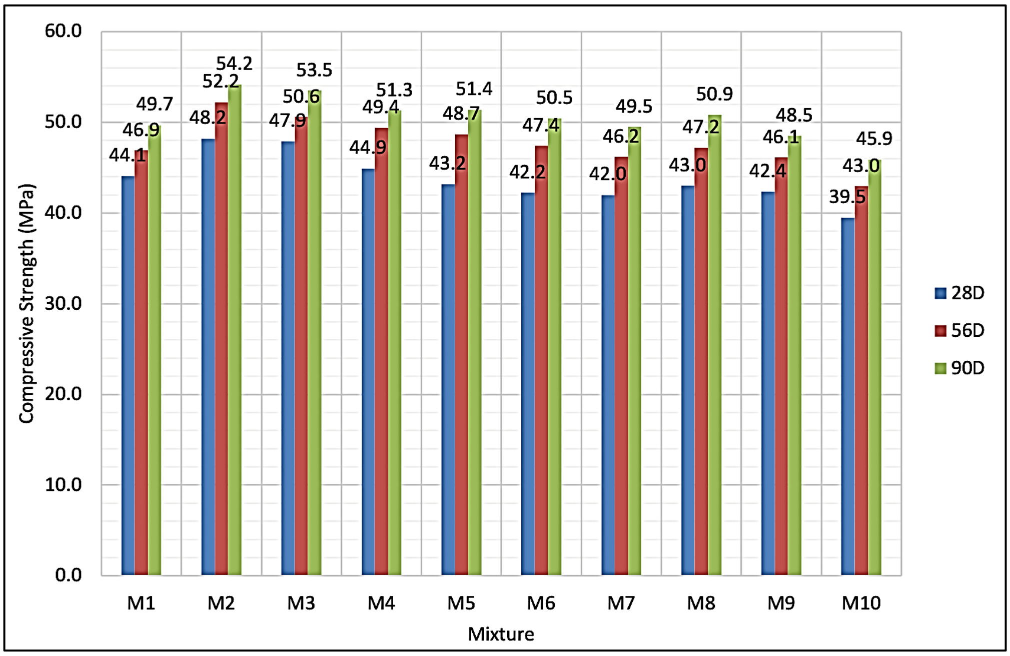

Fig. 6. Compressive strength of concrete mixes at 28, 56, and 90 days [31]

Another researcher, Kunchariyakun and Sukmak [34] who used residue garnet as a filler revealed that the maximum density and compressive strength of mortar was achieved when made wholly of garnet. Usman *et al.,* [35] used garnets to obtain ordinary and self-compacting geopolymer concrete and discovered that the automatically generated (AG) spent garnet proved to be the best candidate for use in Cold Mix Asphalts (CMAs) as compared to manually generated (MG) spent garnet. According to Kanta and Markandeya [42], the results showed that combined spent garnet and used foundry sand can be used as a partial replacement of river sand in the manufacturing of concrete suitable for applications in construction field. On the other hand, there are also researchers who reported that the strength of cement-based composite decreases when blended with spent garnet. According to Phang *et al.,* [43] the approach of integrating spent garnet as partial fine aggregate replacement by weight of sand reduces concrete strength. Excessive use of 30% and 40% spent garnet formed a weak concrete. Future research on the impact of using spent garnet obtained from different type of industry and diverse fineness on the strength performance of cement-based composite is recommended.

4.2 Flexural Strength

The findings of previous researchers outlined in Table 4 showed the increase in flexural strength varies among researchers depending on the different level replacement of spent garnet. It is observed that a large amount of spent garnet up to 30% replacement of sand significantly reduces the flexural strength of concrete. Several studies [24,29] have shown that incorporating spent garnet can improve the flexural strength of concrete at optimal replacement levels. They found that the amount of spent garnet is remarkable in ranges of 20% to 25% and the possibility of attaining above 6.7 MPa depends on selective material and production. The unique characteristics of spent garnet create concrete properties of high density with low porosity, thereby promoting flexural strength. Figure 7 illustrates the flexural strength of lightweight aggregate concrete with spent garnet ratios of 0%, 10%, 20%, 30%, and 40% as documented by Jamaludin *et al.,* [28]. The inclusion of 20% spent garnet leads to an increase in the flexural strength amongst all mixes. High usage of spent garnet does not benefit the flexural strength of the concrete.

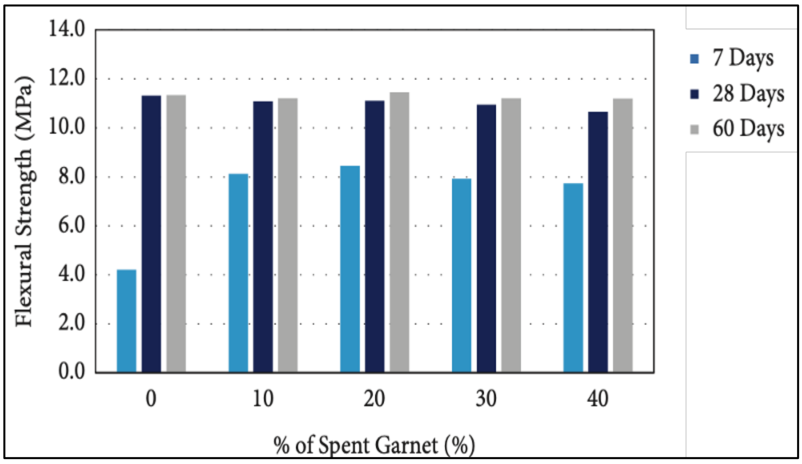

Fig. 7. Flexural strength of lightweight aggregate concrete [29]

Research elsewhere, Ab Kadir *et al.,* [41] claimed that the replacement levels for spent garnet can be up to 40%, as shown in Figure 8 The results revealed that the highest flexural strength obtained was those designated as concrete containing 40% spent garnet. It is evident that the small particles of spent garnet fill in the empty parts within the concrete, resulting in a dense and compact final product. This leads to an improvement in flexural strength. Conversely, Muttashar *et al.,* [21] observed that self-compacting geopolymer concrete (SCGPC) incorporating spent garnet significantly reduced the flexural strength as shown in Figure 9. Excessive use of spent garnet reduces the sand ratio, decreasing the interlocking between fine aggregate and binders. However, the modification of SCGPC incorporating 25% spent garnet offers the greatest flexural strength among the SCGPC specimens incorporating spent garnet. The effective utilization of spent garnet with an appropriate quantity is a viable proposition. The enhancement of flexural strength in concrete, traditionally consisting of 20% to 25% spent garnet, should not be deemed unexpected. In addition, spent garnet particles are typically more angular and rougher in texture compared to rounded river sand particles. By replacing the sand with spent garnet, the concrete can maintain similar properties while reducing the depletion of natural resources and environmental sustainability.

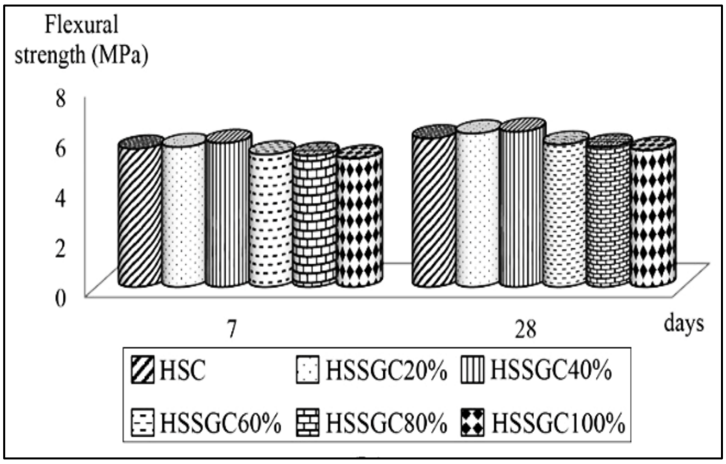

Fig. 8. Flexural strength of high-strength concrete [43]

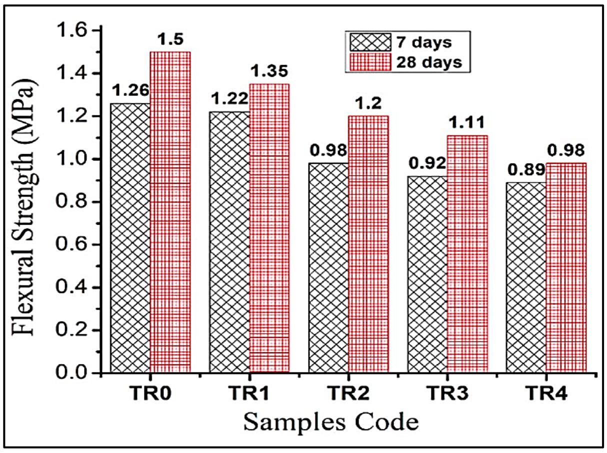

Fig. 9. Flexural strength of geopolymer self-compacting concrete [22]

4.3 Splitting Tensile Strength

It is well-documented (Table 4) that utilization of spent garnet can be a suitable option to reduce the high volume of sand in the concrete proportion. Several researchers [24,43,29] highlighted that the replacement of conventional sand with spent garnet would increase the splitting tensile strength. They expressed the opinion that the use of spent garnet in a concrete mixture with the optimum replacement levels significantly affects the strength. Huseien *et al.,* [23], reported that alkali-activated mortars incorporating fly ash and GBFS, along with 25% spent garnet markedly a notable enhancement in splitting tensile strength. The strength levels experienced a decline once the proportion of spent garnet exceeded 25% in the mix. This observation was confirmed by Jamaludin *et al.,* [28] who investigated the impact of spent garnet on lightweight aggregate concrete as shown in Figure 10. Their findings revealed that the concrete containing 20% spent garnet replacement exhibited superior strength in comparison to the control mixture.

Notably, the strength levels remained slightly drops with the incorporation of 30% and 40% spent garnet. This phenomenon can be attributed to the weakening bonding capacity of the binder paste with the finer spent garnet particles as the amount of spent garnet substitution increased. On the other hand, researcher elsewhere, Zhang *et al.,* [44] pointed out that 40% spent garnet enhanced the internal structure of high strength concrete as compared to the control mix. The uniqueness of the spent garnet physical properties used by each researcher who obtained the waste from different industry, is one of the factors that contribute towards diverse results. The effect of spent garnet as fine aggregate replacement on splitting tensile strength of different types of fibre reinforced concrete, polymer cement concrete, heavyweight concrete, polymer concrete and sulphur concrete is another area to be investigated.

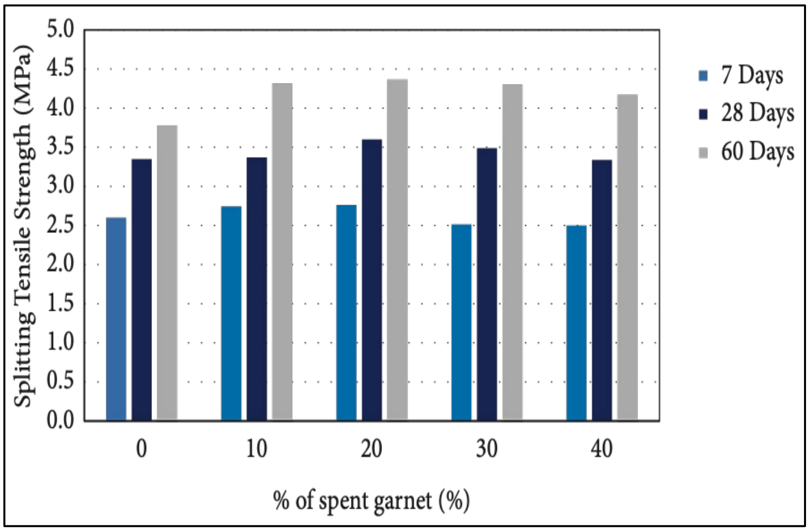

Fig. 10. Splitting tensile strength of lightweight aggregate concrete [29]

The exploration of the coal bottom ash-based concrete incorporating ultrafine spent garnet was also reported by Wan Chik *et al.,* [30]. Figure 11 reveals that increasing the levels of ultrafine coal bottom ash (uCBA) and spent garnet in the mixture leads to a decrease in the splitting tensile strength. Certain mixtures, a combination of 3% uCBA and 10%, 20%, and 30% spent garnet, respectively, demonstrate superior strength than the control sample. The findings suggest that the incorporation of uCBA alongside spent garnet as a partial replacement in concrete leads to enhanced strength at reduced substitution rates due to the limited expansion of Calcium Silicate Hydrate (C-S-H) gel in comparison to higher levels of replacement. The use of uCBA and spent garnet in concrete yields a denser mixture than conventional concrete.

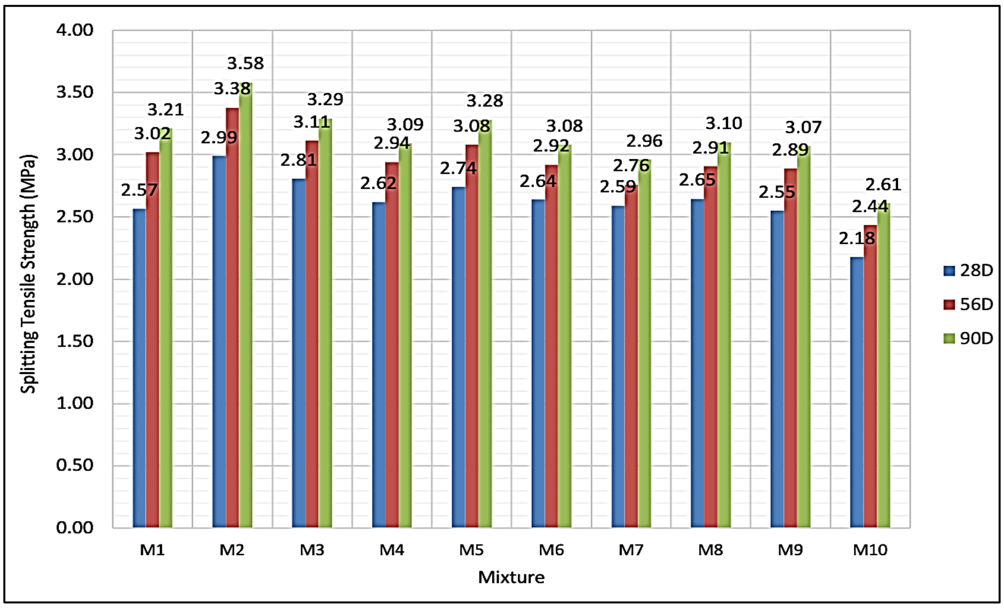

Fig. 11. Splitting tensile strength of concrete specimens [31]

In contrast, Muttashar *et al.,* [21] claimed that the utilization of spent garnet in self-compacting geopolymer concrete led to a significant decrease in the splitting tensile strength. Nevertheless, the findings indicated that the strength of self-compacting geopolymer concrete was enhanced by the presence of 25% spent garnet compared to those of mixtures with 50%, 75%, and 100% spent garnet. The decrease in tensile strength observed with the gradual inclusion of spent garnet in the mixture was ascribed to the weakened bonding between the finer spent garnet particles and the binder paste. The integration of spent garnet into concrete blends has the potential to augment the splitting tensile strength when utilized at ideal substitution limits. Research reveals that the recommended substitution amount for spent garnet typically falls within the range of 20% to 25% of the weight of sand. Within this interval, notable enhancements in strength become apparent. In addition, combining spent garnet with other supplementary cementitious materials can further enhance the strength of concrete.

5. Durability Related Properties

5.1 Water Absorption

Integration of spent garnet influences the water absorption of cement-based composite material. According to Huseien *et al.,* [23], water absorption of mortar containing spent garnet ranges between 8 to 10%. As shown in Figure 12, the permeability of alkali-activated mortars tends to drop to 8.6% with 25% of spend garnets compared to 9.8% observed with the control sample. However, with increased content of spend garnets from 25% to 50%, 75% and 100%, the permeability slightly increased to 9.6, 9.9, and 10.1%, respectively. Jamaludin *et al.,* [28] reported that the 20% of replacement spent garnet in lightweight concrete demonstrates the lowest value of water absorption amongst all mixes. This trend is illustrated in Figure 13 whereby a perfect blend of fine textured spent garnet in concrete contributes towards the densification of mortar internal structure owing to its filler effect resulting in lower water absorption. Zhang *et al.,* [46] added that the decreases in water absorption are mostly due to the inner structure of cement composite that gradually becomes compact. However, overuse of this waste material increases the water absorption of the hardened specimen. The availability of extra water in the mix when too much of spent garnet is integrated causes formation of many pores in the hardened composite. The presence of these pores tends to increase the quantity of water absorbed. This trend has been reported by Huseien *et al.,* [23] and Jamaludin *et al.,* [28].

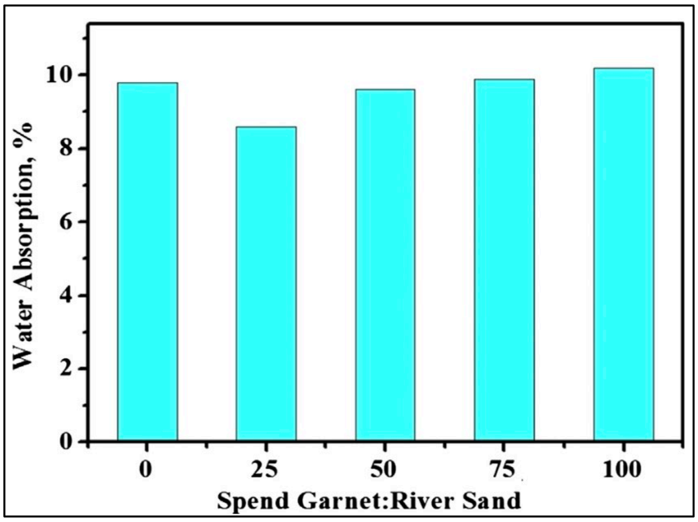

Fig. 12. Water absorption in alkali-activated mortar [24]

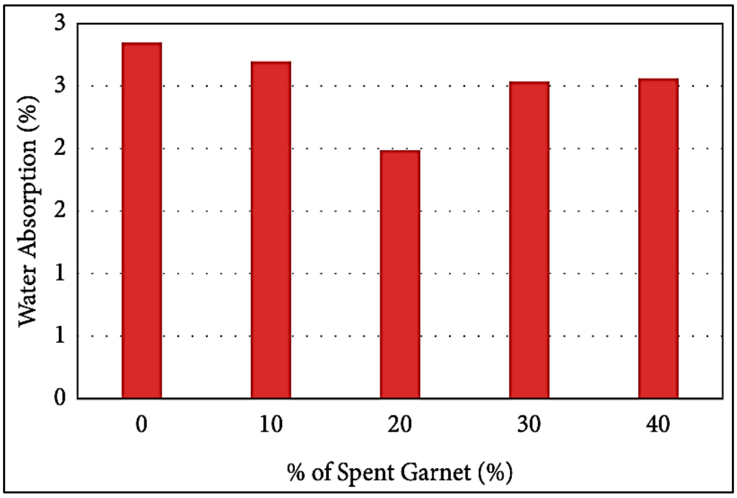

Fig. 13. Water absorption of lightweight aggregate concrete [29]

5.2 Resistance to Chemical Attack

Research conducted by Huseien *et al.,* [23] on the use of spent garnets as sand replacement in alkali-activated mortars containing fly ash and ground blast furnace slag (GBFS) discovered that replacing river sand by 25% of spend garnets improved resistance to sulphuric acid attack. Another researcher elsewhere Sani *et al.,* [25] noted that self-compacting geopolymer concrete that were produced by integrating spent garnet as sand replacement demonstrate greater weight loss in contrast to control specimen without spent garnet throughout the exposure period in acidic environment. Meanwhile, another researcher Jamaludin *et al.*, [28] reported that the ability of lightweight aggregate concrete to withstand the acidic attack is enhanced with the 20% replacement of spent garnet. As illustrated in Figure 14 and Figure 15, the specimen consisting of 20% spent garnet exhibits the lowest mass loss and strength reduction after being immersed in hydrochloric acid solution for 28 days and 60 days indicating its better durability in comparison to control specimen. The differences in the result reported by the researchers are probably due to the dissimilar types of acid used and the types of concrete that been investigated. Further investigation on behavior of cement-based concrete and cement free concrete containing spent garnet upon exposure to different types of acid environment would contribute towards better understanding regarding its performance in aggressive environment.

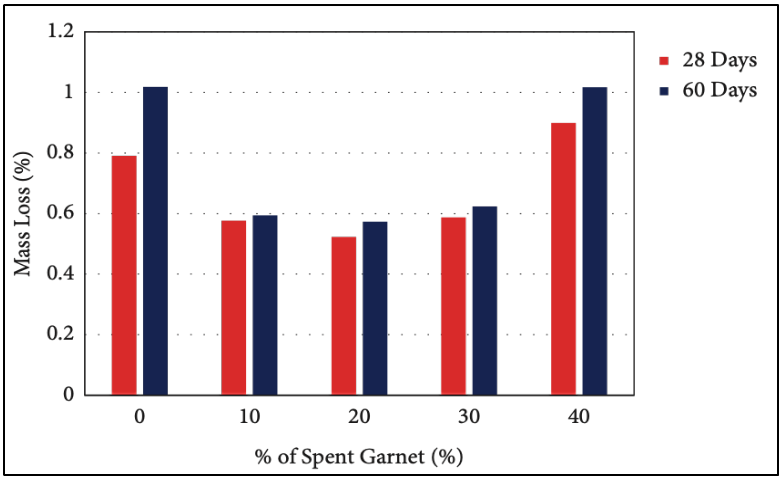

Fig. 14. Mass loss due to acid attack [29]

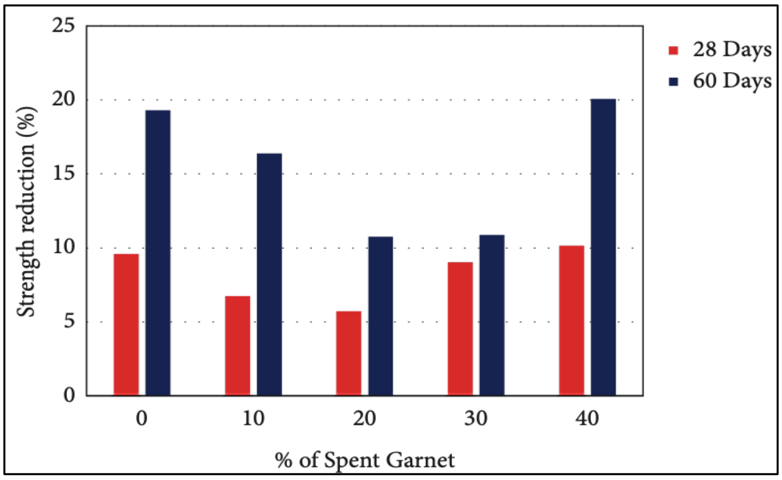

Fig. 15. Strength reduction due to acid attack [29]

6. Other Properties

Upon exposure to elevated temperature, concrete formed of a suitable percentage of spent garnet exhibits better performance against fire attack demonstrating lower mass and strength loss. The superior performance of concrete when blended with spent garnet has been reported by Ab Kadir *et al.,* [41] and Jaafar *et al.,* [22] As shown in Figure 16, it can be seen that the residual compressive strength of spent garnet concrete is higher than that of the control specimens when exposed to various elevated temperatures. Concrete with 40% spent garnet offered better residual compressive strength than the control specimens. However, the strength decreased upon further heating to 400°C but remained slightly higher than that of control specimens. Another researcher Jaafar *et al*., [22] also claimed that the results (Figure 17) show a noticeable decrease in the compressive strength of the concrete subjected to increased temperatures of 700°C. Upon exposure to 700°C, lightweight aggregate concrete formed using 20% spent garnet experience lower strength loss amongst all mixes. Whereas mix formed of 50% spent garnet undergoes highest strength loss of all other mixes.

According to Tawia *et al*., [45] upon exposure to temperature from 400°C to 800°C, concrete experience maximum loss strength due dehydration effect. Decomposition of C-S-H gel results in concrete strength declination and increased porosity [46]. When compared between the mixes, concrete that contained 20% spent garnet recorded lower percentages of strength loss. Both studies highlighted the potential of spent garnet in concrete enhanced performance under heat exposure. Utilization of spent garnet offers greater stability of the concrete exposed to high temperatures. Additional investigation on the fire resistance of special concrete consisting spent garnet from different sources as fine aggregate replacement and the application of different cooling method should be carried out.

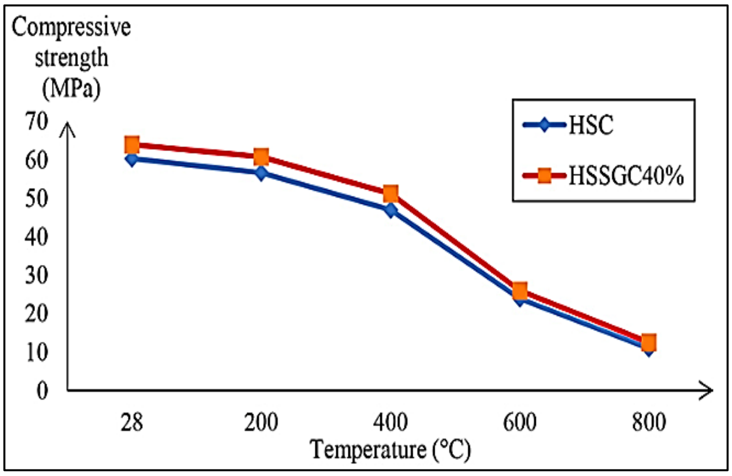

Fig. 16. Residual compressive strength of concrete when exposed to elevated temperatures [43]

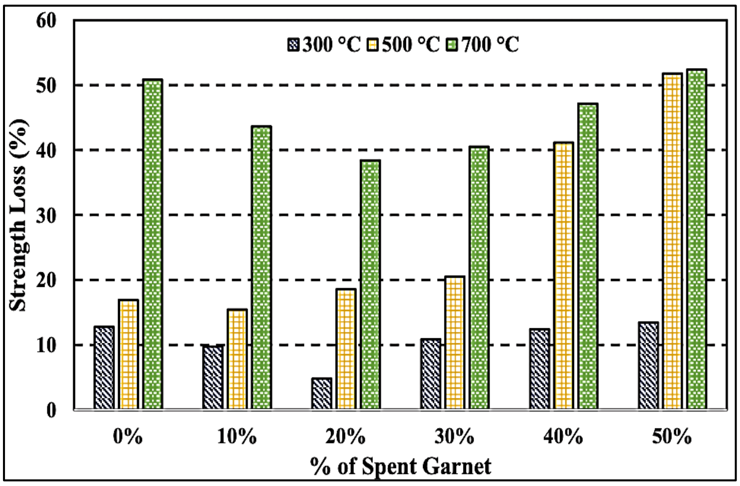

Fig. 17. Strength loss after exposure to elevated temperature [23]

Other than that, research that has been conducted discovered that the integration of a suitable amount of spent garnet lowers the drying shrinkage of concrete. Research by Huseien *et al.,* [23], in the entire test duration, the drying shrinkage of the control specimen was higher than the one composed of spent garnet. As can be seen in Figure 18, the inclusion of 25% and 50% spent garnet resulted in lower drying shrinkage value of the composite material than the control mix. This positive contribution is attributed to the nature of fine garnet particles that filled the micro-pores of the mix which optimize the pore structures resulting in lower value of drying shrinkage.

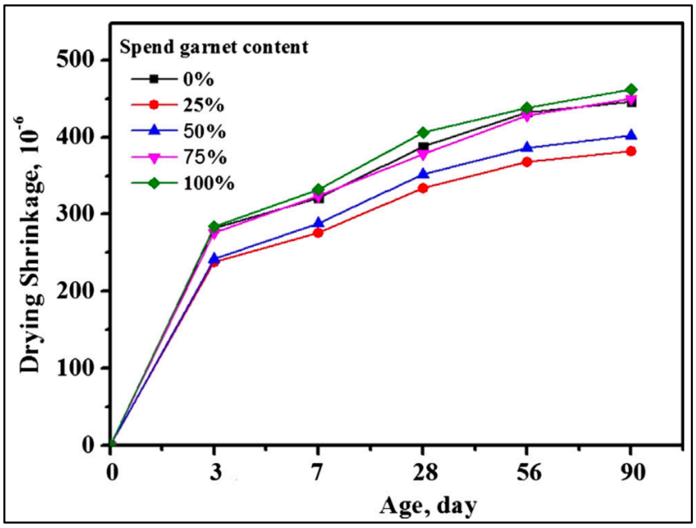

Fig. 18. Drying shrinkage of alkali-activated mortars [23]

Total replacement of sand with spent garnet causes more voids formed due to the presence of additional water resulting in higher drying shrinkage at all curing age. The drying shrinkage of different types of special concrete such as lightweight aggregate concrete, self-compacting concrete and high strength concrete consisting diverse percentage of spent garnet is among the interesting area to be ventured. The effect of using spent garnet originating from different industrial activity towards drying shrinkage of composite material is another area that could be explored in future research.

7. Conclusion

In conclusion, the incorporation of spent garnet as a sand replacement in concrete emerges as a promising avenue with multifaceted benefits. Integration of spent garnet as sand replacement improves the workability of concrete and mortar. A suitable blend of spent garnet as a sand replacement, not more than 25% up positively influences the mechanical properties of concrete, enhancing its strength via the filler effect. Excessive use of spent garnet affects the mix workability resulting in concrete strength declination. Replacing sand with a certain quantity of spent garnet forms a more compact concrete resulting in lower water absorption value. Introducing a suitable percentage of spent garnet of not more than 20% forms concrete with better fire resistance properties. In line with SDGs, integrating waste in production of construction material contributes towards lesser reliance of natural sand and minimize waste disposal for a better living environment of the human population. This review provides an in-depth evaluation of the feasibility of incorporating spent garnet into construction materials. Thorough analyses of the physical and mechanical properties of these composites highlight the potential benefits and limitations associated with spent garnet utilization.

Therefore, more research is recommended to be carried out on exploring the potential utilization of spent garnet for production of polymer concrete, fibre reinforced concretes, manufactured lightweight aggregate concrete and aerated concrete. The effect of using this waste as sand replacement on the mechanical and durability of these special concretes remains to be discovered. The performance of industrial or agricultural pozzolanic ash blended cement concrete when diverse percentages of spent garnet are used as sand replacement remains to be investigated. The performance of concrete containing spent garnet when exposed to the seawater environment is yet to be answered. The behavior of seawater mixed concrete and mortar containing spent garnet as sand replacement is another interesting area to be ventured into. In conclusion, the review consolidates the existing knowledge on spent garnet in construction, delivering valuable insights for researchers and industry experts aiming to explore sustainable, innovative solutions in materials science and waste management.

Acknowledgement
The authors extend their gratitude to the Kementerian Pendidikan Tinggi Malaysia dan Universiti Malaysia Pahang Al-Sultan Abdullah for supporting them in conducting this research via FRGS/1/2023/STG05/UMP/02/4) and RDU230142 respectively.

References

[1] Ahmed, Mohammed Elhaj Alsoufi Mohammed. "Engineering Performance of Cement Mortar Cubes Containing Percentage of Date Palm Fibers and Leaf Ash." *Advanced Research in Applied Sciences and Engineering Technology* 30, no. 1 (2023): 203-227. https://doi.org/10.37934/araset.30.1.203227
[2] Mohamad, Nabilla, Khairunisa Muthusamy, Rahimah Embong, Andri Kusbiantoro. and Mohd Hanafi Hashim"Environmental impact of cement production and solutions: a review." *Materials Today: Proceedings* 48, (2021):741–46. https://doi.org/10.1016/j.matpr.2021.02.212
[3] Jamaludin, Nur Farah Aziera, Khairunisa Muthusamy, Mohd Faizal Md Jaafar, Zuraina Ali, Zaiton Abdul Majid. and Mohamed A. Ismail. "Preliminary investigation on spent garnet as a novel supplementary cementitious material." *Construction and Building Materials* 451, (2024):1–16. https://doi.org/10.1016/j.conbuildmat.2024.138789
[4] GMI. *Construction aggregates market size - By product (sand, gravel, crushed stone), by application (residential, commercial, nonbuilding construction), industry analysis report & global forecast, 2023-2032*. Global Market Insight, 2023.
[5] Designing Buildings the Constructions Wiki. *Construction Aggregates Market 2016-2024*. 2020.
[6] Jasni, Sofia Adibah, Khairunisa Muthusamy, Hanis Nadiah Ruslan, Hussein Hamada, and Ezahtul Shahreen Ab Wahab. "Use of seashell as cement replacement in construction material: A review." *Construction* 4, no. 1 (2024): 7-20. https://doi.org/10.15282/construction.v4i1.10001
[7] Haldar, Swapan Kumar. *Introduction to mineralogy and petrology*. Elsevier, 2020. https://doi.org/10.1016/B978-0-12-820585-3.00004-1
[8] Australian Government Geoscience Australia. *Garnet*. 2018.
[9] Oh, Tae-Min, Gun-Wook Joo, Yohan Cha, and Gye-Chun Cho. "Effect of garnet characteristics on abrasive waterjet cutting of hard granite rock." *Advances in Civil Engineering* 2019, no. 1 (2019): 5732649. https://doi.org/10.1155/2019/5732649
[10] GMA Garnet. *Why use garnet as an abrasive for waterjet cutting instead of other substitutes?*. 2023.
[11] Baxter, Ethan F., Mark J. Caddick, and Jay J. Ague. "Garnet: Common mineral, uncommonly useful." *Elements* 9, no. 6 (2013): 415-419. https://doi.org/10.2113/gselements.9.6.415
[11] Jamaludin, Nur Farah Aziera, Khairunisa Muthusamy, Nurul Nabilah Isa, Mohd Faizal Md Jaafar, and Norhaiza Ghazali. "Use of spent garnet in industry: A review." *Materials Today: Proceedings* 48 (2022): 728-733. https://doi.org/10.1016/j.matpr.2021.02.210
[12] Schumann, Walter. *Gemstones of the World*. Sterling Publishing Company, Inc., 2009.
[13] Jaganmohan, *Madhumitha. Production volume of garnets in India from financial year 2012 to 2022, with estimates until 2024*. Statista, 2024.
[14] Klimpel, Franziska, Michael Bau, and Torsten Graupner. "Potential of garnet sand as an unconventional resource of the critical high-technology metals scandium and rare earth elements." *Scientific Reports* 11, no. 1 (2021): 5306. https://doi.org/10.1038/s41598-021-84614-x
[15] Muttashar, Habeeb Lateef, Nazri Bin Ali, Mohd Azreen Mohd Ariffin, and Mohd Warid Hussin. "Microstructures and physical properties of waste garnets as a promising construction materials." *Case Studies in Construction Materials* 8 (2018): 87-96. https://doi.org/10.1016/j.cscm.2017.12.001
[16] Zulkifli, Ikmal, and Shahrul Niza Mokhatar. "Performance of Spent Garnet as sand replacement in concrete at high temperature." *Recent Trends in Civil Engineering and Built Environment* 3, no. 1 (2022): 731-738. https://doi.org/10.30880/rtcebe.2022.03.01.087

[17] Tafesse, Shitaw, Yidnekachew Esayas Girma, and Eliyas Dessalegn. "Analysis of the socio-economic and environmental impacts of construction waste and management practices." *Heliyon* 8, no. 3 (2022). https://doi.org/10.1016/j.heliyon.2022.e09169

[18] Fedorchuk, Y. M., and V. V. Matvienko. "Applicability assessment of the resource-saving method for recovering garnet sand abrasivity." In *IOP Conference Series: Earth and Environmental Science*, vol. 459, no. 5, p. 052082. IOP Publishing, 2020. https://doi.org/10.1088/1755-1315/459/5/052082

[19] Abbatelli, Daniele. *Material flows in the waterjet industry: An environmental perspective*. Master Diss., Environmental Technology and Mangement, Linkoping University, 2014.

[20] Chiama, Kristen, Morgan Gabor, Isabella Lupini, Randolph Rutledge, Julia Ann Nord, Shuang Zhang, Asmaa Boujibar, Emma S. Bullock, Michael J. Walter, Kerstin Lehnert, Frank Spear, Shaunna M. Morrison, and Robert M. Hazen "The secret life of garnets: a comprehensive, standardized dataset of garnet geochemical analyses integrating localities and petrogenesis." *Earth System Science Data Discussions* 2023 (2023): 1-42. https://doi.org/10.5194/essd-2023-45

[21] Muttashar, Habeeb Lateef, Mohd Azreen Mohd Ariffin, Mohammed Noori Hussein, Mohd Warid Hussin, and Shafiq Bin Ishaq. "Self-compacting geopolymer concrete with spend garnet as sand replacement." *Journal of Building Engineering* 15 (2018): 85-94. https://doi.org/10.1016/j.jobe.2017.10.007

[22] Jaafar, Mohd Faizal Md, Khairunisa Muthusamy, Nur Farah Aziera Jamaludin, Sofia Adibah Jasni, and Fahrizal Zulkarnain. "Fire resistance of lightweight aggregate concrete containing spent garnet as partial fine aggregate replacement." *The Open Construction & Building Technology Journal* 18, no. 1 (2024). https://doi.org/10.2174/0118748368294704240324143756

[23] Huseien, Ghasan Fahim, Abdul Rahman Mohd Sam, Kwok Wei Shah, A. M. A. Budiea, and Jahangir Mirza. "Utilizing spend garnets as sand replacement in alkali-activated mortars containing fly ash and GBFS." *Construction and Building Materials* 225 (2019): 132-145. https://doi.org/10.1016/j.conbuildmat.2019.07.149

[24] Aletba, Salam R., Norhidayah Abdul Hassan, Eeydzah Aminudin, Ramadhansyah Putra Jaya, and Ahmed Abdulameer Hussein. "Marshall properties of asphalt mixture containing garnet waste." *Journal of Advanced Research in Materials Science* 43, no. 1 (2018): 22-27.

[25] Sani, WNH Mior, Azman Mohamed, H. Md Nor, N. A. S. Kamarudin, N. H. A. Khalid, AR Mohd Sam, and R. Ab Rashid. "Characterization of soil mixed with garnet waste for road shoulder." In *IOP Conference Series: Earth and Environmental Science*, vol. 220, no. 1, p. 012052. IOP Publishing, 2019. https://doi.org/10.1088/1755-1315/220/1/012052

[26] Lim, Nor Hasanah Abdul Shukor, Noor Fazura Najihah Alladin, Hossein Mohammadhosseini, Nur Farhayu Ariffin, and Ain Naadia Mazlan. "Properties of mortar incorporating spent garnet as fine aggregates replacement." *International Journal of Integrated Engineering* 12, no. 9 (2020): 96-102. https://doi.org/10.30880/ijie.2020.12.09.012

[27] Sukmak, Patimapon, Gampanart Sukmak, Suksun Horpibulsuk, Sippakarn Kassawat, Apichat Suddeepong, and Arul Arulrajah. "Improved mechanical properties of cement-stabilized soft clay using garnet residues and tire-derived aggregates for subgrade applications." *Sustainability* 13, no. 21 (2021): 11692. https://doi.org/10.3390/su132111692

[28] Jamaludin, Nur Farah Aziera, Khairunisa Muthusamy, Mohd Faizal Md Jaafar, Ramadhansyah Putra Jaya, and Mohamed A. Ismail. "Performance of palm oil clinker lightweight aggregate concrete comprising spent garnet as fine aggregate replacement." *Advances in Civil Engineering* 2022, no. 1 (2022): 9674096. https://doi.org/10.1155/2022/9674096

[29] Muthusamy, Khairunisa, Nur Farah Aziera Jamaludin, Adibah Zulaikha Zainuddin, Mohd Faizal Md Jaafar, and Mehmet Serkan Kirgiz. "Effect of spent garnet waste as partial fine aggregate replacement on properties of high strength lightweight aggregate concrete." *Key Engineering Materials* 912 (2022): 17-23. https://doi.org/10.4028/p-8u5o6b

[30] Wan Chik, Wan Muhammad Eddie Khusyairi, Shahrul Niza Mokhatar, Nor Hazurina Othman, Ahmed Mokhtar AAlbshir Budiea, and Khairunisa Muthusamy. "The exploration of the characteristics of concrete incorporating ultrafine coal bottom ash and spent garnet." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 36, no. 2 (2024): 164-175. https://doi.org/10.37934/araset.36.2.164175

[31] Yusoff, A. R. M., S. N. Mokhatar, A. M. A. Budiea, and S. J. S. Hakim. "A review: study on spent garnet as construction material." *International Journal of Integrated Engineering* 14, no. 5 (2022): 73-80. https://doi.org/10.30880/ijie.2022.14.05.008

[32] Giergiczny, Zbigniew, and Anna Król. "Immobilization of heavy metals (Pb, Cu, Cr, Zn, Cd, Mn) in the mineral additions containing concrete composites." *Journal of hazardous materials* 160, no. 2-3 (2008): 247-255. https://doi.org/10.1016/j.jhazmat.2008.03.007

[33] Caporuscio, F. A., B. L. Scott, H. Xu, and R. K. Feller. "Garnet nuclear waste forms–Solubility at repository conditions." *Nuclear Engineering and Design* 266 (2014): 180-185. https://doi.org/10.1016/j.nucengdes.2013.10.029

[34] Kunchariyakun, Kittipong, and Patimapon Sukmak. "Utilization of garnet residue in radiation shielding cement mortar." *Construction and Building Materials* 262 (2020): 120122. https://doi.org/10.1016/j.conbuildmat.2020.120122

[35] Usman, Kabiru Rogo, Mohd Rosli Hainin, Mohd Khairul Idham Mohd Satar, Muhammad Naqiuddin Mohd Warid, Aliyu Usman, Zaid Hazim Al-Saffar, and Munder Abdullah Bilema. "A comparative assessment of the physical and microstructural properties of waste garnet generated from automated and manual blasting process." *Case Studies in Construction Materials* 14 (2021): e00474. https://doi.org/10.1016/j.cscm.2020.e00474

[36] Balasubramaniyan, C., K. Rajkumar, B. Suresh Krishnan, and A. Arun. "Performance evaluation of abrasive water jet machining on spent garnet reinforced hybrid composite." *Materials Today: Proceedings* 98 (2024): 16-20. https://doi.org/10.1016/j.matpr.2023.08.306

[37] Mior Sani, Wan Noor Hin, Ramadhansyah Putra Jaya, Khairil Azman Masri, Kushendarsyah Saptaji, and Anmar Dulaimi. "Exploring the chemical properties and microstructural characterisations of hybrid asphalt binders for enhanced performance." *Discover Applied Sciences* 6, no. 4 (2024): 193. https://doi.org/10.1007/s42452-024-05868-4

[38] Gonçalves, J. P., L. M. Tavares, R. D. Toledo Filho, E. M. R. Fairbairn, and E. R. Cunha. "Comparison of natural and manufactured fine aggregates in cement mortars." *Cement and Concrete Research* 37, no. 6 (2007): 924-932. https://doi.org/10.1016/j.cemconres.2007.03.009

[39] Mehta, Povindar K., and Paulo Monteiro. *Concrete: microstructure, properties, and materials*. *McGraw-Hill*, 2014.

[40] Morizki, Morizki, and Imam Setyohadi. "Pengaruh solidifikasi limbah garnet dengan beton terhadap kuat tekan beton." *Sigma Teknika* 1, no. 1 (2018): 252-258.

[41] Ab Kadir, Mariyana Aida, Mohammad Iqbal Khiyon, Abdul Rahman Mohd. Sam, Ahmad Beng Hong Kueh, Nor Hasanah Abdul Shukor Lim, Muhammad Najmi Mohamad Ali Mastor, Nurizaty Zuhan, and Roslli Noor Mohamed. "Performance of spent garnet as a sand replacement in high-strength concrete exposed to high temperature." *Journal of Structural Fire Engineering* 10, no. 4 (2019): 468-481. https://doi.org/10.1108/JSFE-10-2018-0025

[42] Kanta, Naga Rajesh, and Markandeya Raju Ponnada. "Performance of spent garnet sand and used foundry sand as fine aggregate in concrete." *World Journal of Engineering* 19, no. 5 (2022): 632-638. https://doi.org/10.1108/WJE-10-2020-0514

[43] Phang, Zhi Qian, Shahrul Niza Mokhatar, and Ahmed Mokhtar Albshir Budiea Albshir Budiea. "Effects of spent garnet on the compressive and flexural strengths of concrete." *Recent Trends in Civil Engineering and Built Environment* 3, no. 1 (2022): 1948-1957.

[44] Zhang, Weifeng, Xiaowei Gu, Jingping Qiu, Jianping Liu, Yunqi Zhao, and Xiaohui Li. "Effects of iron ore tailings on the compressive strength and permeability of ultra-high performance concrete." *Construction and Building Materials* 260 (2020): 119917. https://doi.org/10.1016/j.conbuildmat.2020.119917

[45] Tahwia, Ahmed M., Mohamed Abd Ellatief, Ghada Bassioni, Ashraf M. Heniegal, and Mohamed Abd Elrahman. "Influence of high temperature exposure on compressive strength and microstructure of ultra-high performance geopolymer concrete with waste glass and ceramic." *Journal of Materials Research and Technology* 23 (2023): 5681-5697. https://doi.org/10.1016/j.jmrt.2023.02.177

[46] Jia, Zijian, Chun Chen, Jinjie Shi, Yamei Zhang, Zhengming Sun, and Peigen Zhang. "The microstructural change of CSH at elevated temperature in Portland cement/GGBFS blended system." *Cement and Concrete Research* 123 (2019): 105773. https://doi.org/10.1016/j.cemconres.2019.05.018