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Influence of seawater mixing on fresh and mechanical properties of oil palm shell lightweight aggregate concrete containing spent garnet

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Abstract. The rapid advancement in construction practices has led to a higher demand for natural aggregates in the production of concrete. Simultaneously, there has been an increase in pollution due to the improper disposal of industrial waste. Effective waste management has become imperative to prevent environmental harm. A sustainable solution involves incorporating waste materials such as oil palm shells (OPS) from the palm oil industry and spent garnet from shipbuilding activities into concrete production. This research aims to explore the impact of introducing spent garnet as a partial substitute for sand on the fresh and hardened properties of lightweight aggregate concrete (LWAC) made with OPS, mixed with seawater. Two sets of concrete mixes were prepared, varying the proportion of spent garnet as a partial replacement for fine aggregate, and both seawater and freshwater were used in the mixing process. Laboratory tests were conducted to evaluate workability, oven-dry density, and compressive strength of the concrete. The findings indicate that the workability decreases in freshwater but improves in both freshwater and seawater when spent garnet is added. All mixtures containing spent garnet qualify as LWAC. Notably, seawater-mixed OPS LWAC, with 10 % spent garnet, demonstrates the highest compressive strength. The use of seawater accelerates hydration, enhancing concrete strength compared to freshwater. In conclusion, incorporating spent garnet as a replacement for sand in concrete production results in environmentally friendly OPS LWAC. This approach contributes to waste reduction and minimizes reliance on landfills, promoting sustainable construction practices.

1. Introduction

Concrete, a highly versatile and abundant building material, has seen increased use due to rapid development and the availability of raw materials [1,2]. Society now recognizes the pressing challenge of waste generation and strives to recycle it by incorporating waste materials into concrete [3]. Aggregates, making up about 70 % of concrete mass, are mainly sourced from natural quarries or riverbeds [4]. The growing number of construction projects to meet societal needs has led to extensive depletion of natural resources for aggregate extraction. To combat environmental challenges, various approaches like waste management, reuse, reduction, regeneration, and efficient natural resource use are employed with waste materials. Green concrete construction emphasizes responsible handling of agricultural or industrial waste by integrating them into concrete production. The UN underscores the critical need to enhance freshwater ecosystem resilience for climate change adaptation [5]. Freshwater, a crucial resource, supports ecosystems, economies, biodiversity, and society, highlighted in the international Water Sustainable Development decade (2018 – 2028). However, inadequate global water management leaves around 885 million people without sufficient access to safe drinking water [6]. Alarmingly, 17 countries face extremely high freshwater stress, indicating a severe global decline. Concrete production, consuming 9 % of industrial water, poses a significant challenge, especially when 75 % of this occurs in severely water-stressed regions [7]. Using alternative or non-potable water for concrete-making in water-stressed areas is imperative to mitigate this issue. Hence, there are experts in concrete technology actively investigating the viability of seawater as a substitute water source in the manufacturing of concrete. Malaysia, Indonesia, and Thailand stand out as leading global producers of palm oil [8]. The palm oil industry significantly bolsters the nation's economy, generating employment and foreign exchange earnings. However, this vegetable oil industry generates wastes namely pressed empty fruit bunch, oil palm shells, and others which pollute the environment. The rigid endocarp surrounding the palm kernel, termed palm kernel shell or OPS, is often a result of this extraction process [9]. OPS is sometimes improperly disposed of in landfills with organic waste, causing environmental issues like air pollution through incorrect burning or incineration, releasing pollutants into the air. Moreover, OPS is considered a sustainable resource; traditionally, it is incinerated for disposal, contributing to the greenhouse effect and adversely affecting the environment [10]. Therefore, utilizing OPS as an aggregate for concrete production has led to the creation of lightweight aggregate concrete. In the pursuit of environmental sustainability, researchers are actively investigating the possibility of incorporating locally generated wastes to develop a more environmentally friendly LWAC.

Garnet, a durable abrasive mineral used in various applications, ends up as waste known as spent garnet after it is thoroughly used [11]. Disposal of spent garnet, often from abrasive blasting, presents environmental risks like landfill and water contamination due to the chemicals in paints and primers it removes. Researchers are investigating the incorporation of spent garnet into construction materials. Budiea et al. [12] examined the use of spent garnet as a substitute for fine aggregate in high-strength concrete, attaining a compressive strength of 87.9 MPa with a 20 % replacement. Murugadoss et al. [13] optimized concrete mixes by substituting spent garnet using response surface methodology (RSM) and RStudio's Program. Skibicki et al. [14], in their assessment of spent garnet as a substitute for natural sand in 3D printed mortar, suggested a maximum replacement of 50 % for optimal printability. Abdul Shukor Lim et al. [15] similarly recommended up to 50 % replacement of spent garnet in mortar to achieve comparable strength and low water absorption. Muttashar et al. [16] delved into the performance of self-compacting geopolymer concrete incorporating spent garnet as a component. More recently, Jamaludin et al. [17] discovered that incorporating 20 % spent garnet enhances the compressive strength of palm oil clinker lightweight aggregate concrete. However, the impact of spent garnet on the performance of seawater-mixed lightweight aggregate concrete remains unexplored. Therefore, this study explores how adding spent garnet and using seawater in LWAC can improve performance, offering eco-friendly solutions to waste management and reducing freshwater usage in construction.

2. Experimental program

2.1. Materials

Grade 53 Ordinary Portland Cement (OPC) was utilized, meeting the requirements specified in ASTM C150/C150M-12 [18]. The fine aggregates used were natural river sand dried at 105 ± 5 °C for 24 hours and sieved to retain particles between 2.36 mm and 150 µm. Drying the sand helps to remove any moisture or water content present in the natural river sand. Table 1 shows the physical properties of river sand and spent garnet obtained from a Malaysian brownfield services factory. The spent garnet, sieved and dried at 105 ± 5 °C for 24 hours, was partially used to replace fine aggregates (particles passing 600 µm and retained on a 150 µm sieve). The particle size distribution of river sand and spent garnet can be

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seen in figure 1. For coarse aggregates, OPS obtained from an oil palm processing mill in West Peninsula Malaysia, was used. The OPS was air-dried and sieved to obtain particles passing 10 mm and retained on a 5 mm sieve. Visual images of OPS and spent garnet can be seen in figure 2. Freshwater and seawater were both utilized for mixing purposes.

Table 1. Physical properties of river sand and spent garnet.

Physical properties	River sand	Spent garnet
Bulk density (kg/m^3)	1541	2354
Water Absorption (%)	0.85	6.12
Moisture content (%)	0.42	1.06
Specific gravity	2.77	3.75
Fineness modulus	3.85	2.79

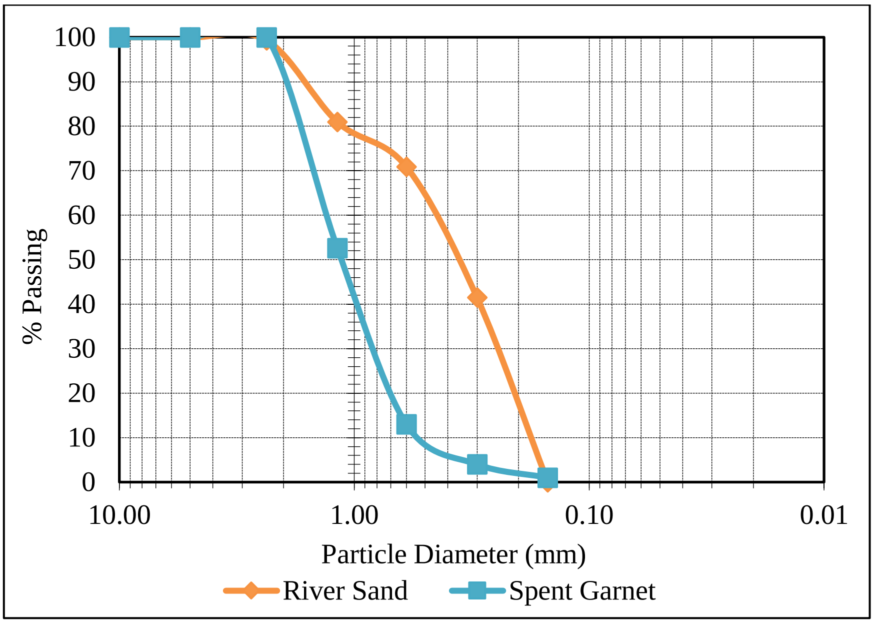

Figure 1. Particle size distribution for river sand and spent garnet.

(a)

(b)

Figure 2. Materials (a) OPS (b) Spent garnet.

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2.2. Concrete mix proportion and testing
Two sets of concrete mixtures, denoted as freshwater (FW) and seawater (SW), were used in this experimental work. The first set, FW mixture, was prepared using mixing water obtained from freshwater sources and served as reference specimens. The second set, SW mixture, was prepared using mixing water collected from the sea. In the first set, labeled FW (0 – 30 %) mixtures, fine aggregate was substituted with spent garnet particles at 0 %, 10 %, 20 %, and 30 %. The second set, labeled as SW (0 – 30 %) mixtures, encompassed various proportions of spent garnet ranging from 0 % to 30 %. The water-to-cement ratio was consistently maintained at 0.55 for all mixtures. To ensure proper curing, all specimens underwent water curing. The specific mixture proportions are meticulously outlined in table 2.

Table 2. Mix proportion (kg/m^3) of OPS LWAC.

Mixes	Sand	Spent garnet	OPS	OPC	Freshwater	Seawater
FW0 (0%)	750	-	350	540	297	-
FW10(10%)	675	75	350	540	297	-
FW20(20%)	600	150	350	540	297	-
FW30(30%)	525	225	350	540	297	-
SW0 (0%)	750	-	350	540	-	297
SW10 (10%)	675	75	350	540	-	297
SW20 (20%)	600	150	350	540	-	297
SW30 (30%)	525	225	350	540	-	297

2.3. Concrete testing
The workability of the concrete was evaluated using the slump test, following the guidelines outlined in BS EN 12350-2 [19]. The dry density of the concrete samples was determined in accordance with the ASTM C642 standard [20]. The compressive strength of OPS LWAC was assessed following the procedures specified in the BS EN 12390-3 [21] standard.

3. Results and discussion

3.1. Workability
The slump measurements, ranging from 20 mm to 90 mm across all mixtures, are depicted in figure 3. An observable trend emerged, indicating that an increase in spent garnet proportion resulted in enhanced workability of OPS LWAC. Mehta and Monteiro [22] emphasized that LWAC with a slump falling within the range of 50 mm to 70 mm exhibited workability comparable to normal-weight concrete, which typically slumps between 100 mm to 125 mm. The OPS LWAC mixture without spent garnet exhibited the least cohesiveness compared to those incorporating spent garnet. This heightened workability is attributed to the higher density of spent garnet (2 354 kg/m^3) in contrast to river sand (1 541 kg/m^3). Furthermore, the smaller particle size of the spent garnet contributed to improved workability by enhancing particle bonding on the surface. Similar findings have been reported by prior researchers [23,24]. Variances in workability were observed between mixes prepared with seawater and freshwater. A consistent reduction in workability with the use of seawater aligns with the findings reported by researcher Hussain et al. [25]. This suggests that the relationship between spent garnet and seawater influences the overall workability of OPS LWAC, with seawater introducing complexities that impact the concrete's cohesive properties.

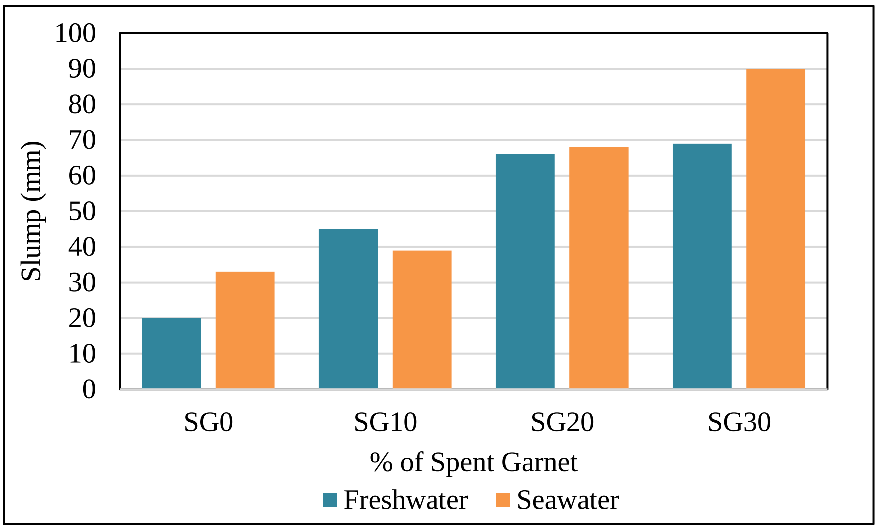

Figure 3. The workability of OPS LWAC containing spent garnet using freshwater and seawater as mixing ingredients.

3.2. Oven dry density

Figure 4 portrays the impact of different levels of spent garnet replacement on the density of OPS LWAC 28 days. The results reveal that the dry density of specimens incorporating spent garnet falls below 1 800 kg/m^3, classifying them as lightweight aggregate concrete. According to ACI 213P [26], for concrete to be classified as LWAC, the average oven-dried density of multiple samples should not exceed 2 000 kg/m^3. Among the tested specimens, the OPS LWAC with 30 % spent garnet replacement demonstrated the highest density value. This can be attributed to the higher bulk density (2 354 kg/m^3) and specific gravity (3.75) of spent garnet compared to river sand. A similar finding was consistently observed and reported throughout the investigation [17]. It is noteworthy that the density of concrete mixed with seawater surpasses that of concrete mixed with freshwater. This discrepancy is attributed to the presence of salts in seawater, impacting the chemical reactions during cement hydration and resulting in distinctive microstructural characteristics [27] that may contribute to a higher density in the concrete.

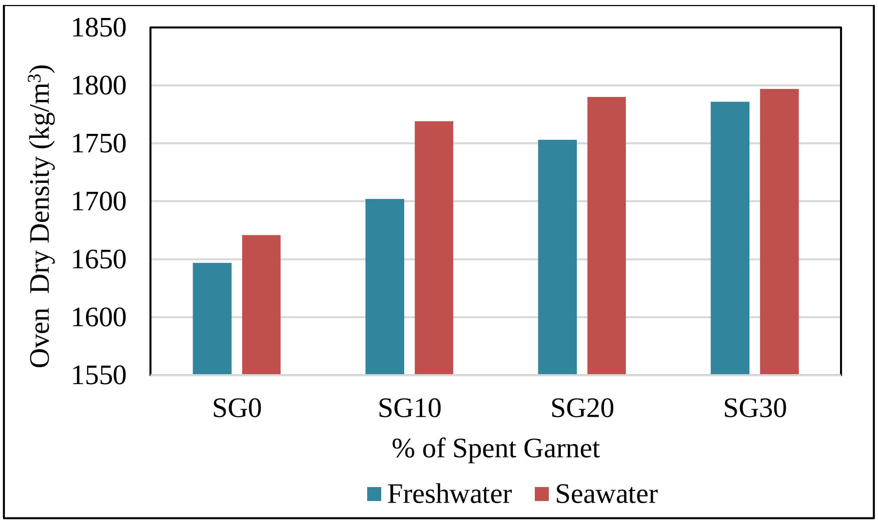

Figure 4. The oven-dry density of OPS LWAC incorporating spent garnet with the use of both freshwater and seawater as mixing ingredients.

3.3. Compressive strength

Figure 5 presents the compressive strength results of OPS LWAC utilizing different proportions of spent garnet as a substitute for sand. Specimens incorporating 10 % spent garnet exhibited superior concrete strength compared to other mixtures at various curing ages when using regular water. This is attributed to the finer aggregates filling gaps within the concrete, resulting in a more compact and robust concrete structure. The enhanced rough and angular texture of spent garnet particles, along with finer particles, contributes to increased compressive strength in OPS LWAC [16,17]. Angular particles efficiently fill gaps, leading to a denser structure that enhances compressive strength by reducing porosity and improving load-bearing capacity. However, caution is advised against excessive use of spent garnet, as its inclusion at 20 % and 30 % resulted in a decrease in compressive strength. Concrete mixed with seawater as the mixing medium exhibited higher strength compared to freshwater-mixed concrete. This phenomenon is attributed to accelerated hydration induced by Cl- ions, reacting with $Ca(OH)_2$ to form $CaCl_2$, a potent accelerator for OPC based binders [28]. Reactions between C_3A in OPC and SO_4 ions in seawater generate gypsum and ettringite, contributing to strength and filling porous media within seawater concrete [29]. Furthermore, chloride ions interact with hydration products, forming compounds like Friedel's salt and Kuzel's salt [30], augmenting the density of the concrete matrix. Due to higher chemical ion content, seawater has a more pronounced effect on concrete strength compared to freshwater. Numerous studies [31,32] have validated that seawater mixes achieve higher initial strength compared to traditional concrete systems. In summary, the relationship between spent garnet and seawater in OPS LWAC is dynamic, with the judicious use of spent garnet influencing compressive strength and the choice of seawater as a mixing medium contributing significantly to concrete strength enhancement.

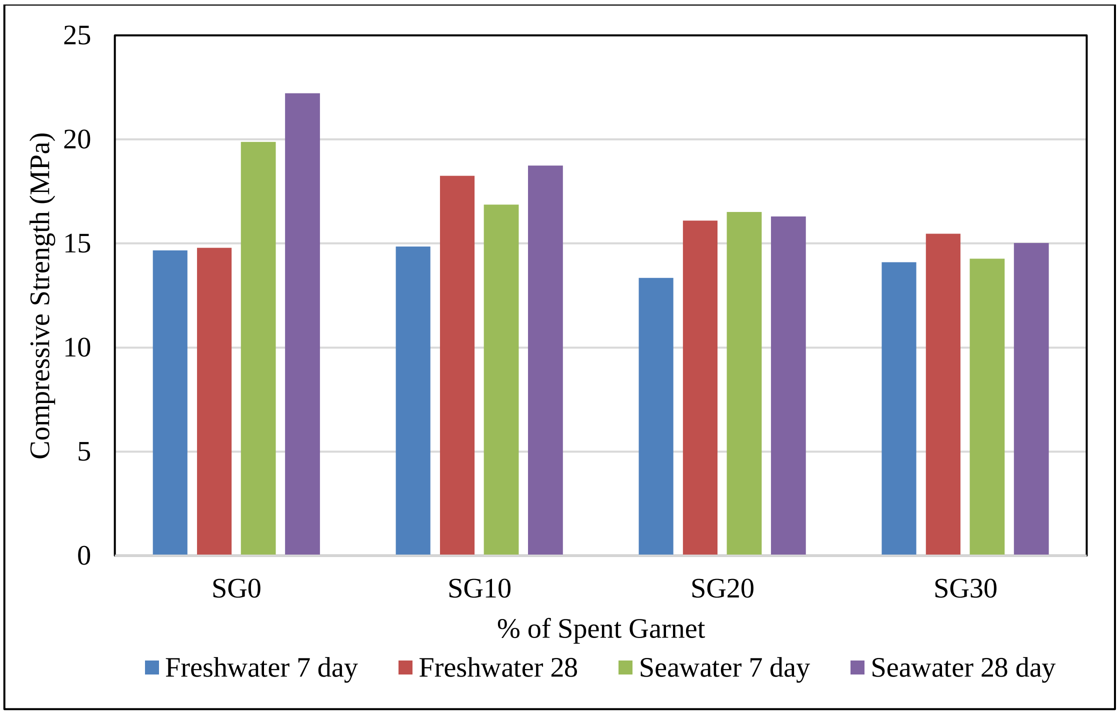

Figure 5. The compressive strength of OPS LWAC containing spent garnet, using both freshwater and seawater as mixing ingredients.

4. Conclusions

The experimental program demonstrates the potential of using spent garnet as a highly effective alternative for partial sand replacement in OPS LWAC especially when incorporating seawater in the mixing processes. The strength outcomes achieved with seawater are comparable to those obtained with freshwater for reference specimens. Firstly, a higher proportion of spent garnet improves the workability of OPS LWAC, and seawater further enhances workability compared to freshwater. Secondly, integrating spent garnet affects the density of OPS LWAC, aligning with LWAC classification standards. A garnet replacement of 30 % results in the highest density, and the use of seawater increases concrete density due to altered chemical reactions. Lastly, incorporating 10 % spent garnet in OPS LWAC significantly boosts compressive strength due to the finer aggregates and angular particle texture, resulting in a denser concrete structure. Additionally, using seawater during mixing enhances concrete strength through accelerated hydration and increased chemical ion content compared to freshwater. Overall, this study highlights the potential of spent garnet and seawater in enhancing the properties and performance of OPS LWAC.

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