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Research Article

Performance of Palm Oil Clinker Lightweight Aggregate Concrete Comprising Spent Garnet as Fine Aggregate Replacement

Nur Farah Aziera Jamaludin,[1] **Khairunisa Muthusamy**,[1] **Mohd Faizal Md Jaafar**,[1] **Ramadhansyah Putra Jaya**,[2] **and Mohamed A. Ismail**[3]

[1]*Faculty of Civil Engineering Technology, Universiti Malaysia Pahang, Lebuhraya Tun Razak, 26300, Gambang, Pahang, Malaysia*
[2]*Department of Civil Engineering, College of Engineering, Universiti Malaysia Pahang, Lebuhraya Tun Razak, 26300, Gambang, Pahang, Malaysia*
[3]*Department of Civil Engineering, Miami College of Henan University, Kaifeng, Henan, China*

Correspondence should be addressed to Khairunisa Muthusamy; khairunisa@ump.edu.my

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The increase in building activity as a result of population expansion has resulted in an overexploitation of aggregate, with disastrous environmental consequences. Simultaneously, the disposal of spent garnet by the shipbuilding industry and palm oil clinker by palm oil mills harms the environment and needs a greater amount of landfill space. Therefore, the purpose of this study was to determine the influence of spent garnet as a fine aggregate substitute on the fresh, mechanical, and durability properties of palm oil clinker concrete. Concrete mixes were created using various percentages of spent garnet as a fine aggregate substitute, including 0%, 10%, 20%, 30%, and 40%. The workability, compressive strength, flexural strength, splitting tensile strength, modulus of elasticity, water absorption, and acid resistance of the water cured concrete were all determined. It was determined that using 20% spent garnet increased the compressive strength of lightweight concrete. The positive filler effect of spent garnet resulted in a densely packed internal structure of concrete, allowing it to have the lowest percentage of water absorption. The same mixtures exhibited the least mass change and strength reduction when exposed to acid solution. The results established that ecologically friendly concrete may be manufactured by including considerable volumes of waste from the shipbuilding and palm oil sectors.

1. Introduction

The Sustainable Development Goals (SDGs) of "Goal 7" are aimed to make sure that everyone can have access to affordable and reliable energy by 2030. This includes expanding infrastructure and upgrading technology to make sure that everyone can get modern and sustainable energy services [1]. The construction sector is one of the industries featured in "Agenda 2030," as it is the least sustainable industry in the world, consuming over half of all nonrenewable resources [2]. Concrete is one of the most essential and commonly utilized building materials in the world nowadays [3]. It is an ideal material for construction because it is strong enough to meet the needs for various applications according to the type of concrete. Zareei et al. [4] reported that 25 billion tons of concrete consumption led to sustainability issues due to the scarcity of natural resources, including aggregates. In comparison, sand, and gravel are the world's most mined resources, with between 32 billion tons and 50 billion tons taken each year [5]. Excessive mining of river sand causes changes in the riverbed, water levels, and flood plains and affects the river ecosystems, navigation systems, and salinity levels [6]. Instabilities in the channel and sedimentation caused by instream mining also cause problems on public facilities such as bridges, pipelines, and utility lines [7]. According to Kuhar [8], global demand for natural aggregates used in concrete manufacturing is expected to expand at an average annual rate of 7.7% through 2022, reaching 66.2 billion metric tons. The rise in aggregate extraction activities from the quarries destroys greenery (which is the habitat of wildlife), changes the natural landscape, and pollutes the environment. The land deprivation causes pollution and affects the biodiversity, posing ecological impact on local neighborhoods and communities [9, 10]. Therefore, utilization of other types of material to function as sand and coarse aggregate in concrete could reduce the quantity of these natural resources reaped from the environment, decrease destruction to green surroundings, and preserve aggregate resources for future use.

Spent garnet waste is a type of waste generated from the shipbuilding industry. Based on the US Geological Survey [11], 140 000 garnets were produced, and 12, 000 tons was exported to other countries, including Malaysia. Garnet is commonly used as an abrasive material for sandblasting ships in Malaysia after the Malaysian shipbuilding industry was recently revealed to be responsible for importing thousands of tons of garnets from outside the country each year [12]. Garnet is an abrasive blasting medium that is a mineral found in crystal metamorphic rocks, and it has a variety of chemical components and colors [13]. Due to its hardness, this material may be recycled several times (between three and five times) for abrasive purposes [14]. The garnet that was no longer useable or practical for blasting purposes would be disposed of as "spent garnet" at landfills [12]. Spent garnet causes many environmental and health hazards because the paint in most ship hulls contains heavy metals like tributyltin (TNT) that leached underground and contaminate soil and underground water [15]. Furthermore, when these products are entered into the rivers through flooding or by run-offs, such garnet wastes cause significant environmental and health dangers such as water pollution [16]. They can threaten the biodiversity of natural ecological environment [12]. An approach that aims to utilize this waste for other purposes rather than disposing it would alleviate this material ending up piled up as an environmental polluting waste.

Malaysia is currently the second-largest producer of palm oil after Indonesia, with the total output accounting for 36% of global demand [17]. In 2019, Malaysia produced 19.86 million tons of palm oil and exported 18.47 million tons [18]. The expansion in the plantation increased the annual production of solid waste such as oil palm shell (OPS), palm oil clinker (POC), and palm kernel fiber [19, 20]. The porous rock-like material known as palm oil clinker (POC) is a by-product obtained during the palm oil and fiber incineration cycle in a boiler at the mill. As palm oil production continues to increase, it is expected that a massive volume of clinker would be produced with little or no commercial value [20, 21]. These waste materials are usually dumped into open fields and landfills [19] and causes water, air, and land pollution [22, 23]. Besides, continuous waste discarding contaminates the soil and impacts the source of groundwater supply [24]. Developing nations such as Malaysia confront several challenges in managing waste sustainably, owing to the rapidly expanding cities and a growing population. Malaysia generated 19,000 tons of debris per day in 2005, with a recycling rate of 5%. The quantity increased to 38,000 tons per day in 2018 even though the recycling rate rose by 17.5% [25]. With limited landfill space and escalating disposal costs, there is an urgent need to address waste management and reduce environmental and human impacts. Hence, integrating POC as coarse aggregate and spent garnet as partial sand replacement in concrete material would reduce the natural aggregate usage and, at the same time, minimize adverse environmental impacts.

Table 1: Physical properties of POC.

Physical properties	POC
Bulk density (kg/m^3)	945.66
Water absorption (%)	10.19
Moisture content (%)	1.87
Aggregate impact value (%)	49.39
Aggregate crushing value (%)	45.54
Los Angeles abrasion value (%)	58.70

Figure 1: Large chunk of POC.

Figure 2: Spent garnet.

2. Materials and Methods

2.1. Materials and Properties. In this study, the binder used was OPC with ASTM C150 [24], classified as Type 1 binder material in the concrete. The properties of POC, which has been used as a lightweight coarse aggregate in this research, are presented in Table 1. Large chunks of POC were collected from a dumping site in a local palm oil mill. POC's large

Table 2: Physical properties of river sand and spent garnet.

Physical properties	River sand	Spent garnet
Bulk density (kg/m^3)	1541	2006
Water absorption (%)	0.85	6.12
Moisture content (%)	0.42	1.06
Specific gravity	2.77	3.75
Fineness modulus	3.85	2.79

Table 3: 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
Calcium oxide (CaO)	-
Manganese (II) oxide (MnO)	1.03
Titanium dioxide (TiO_2)	1.53

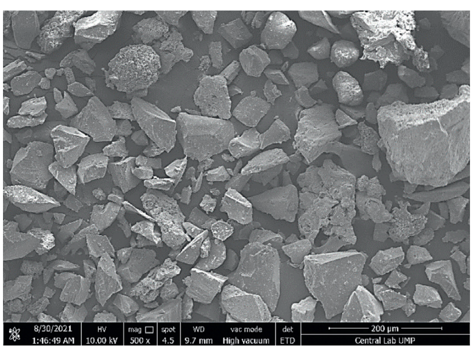


Figure 3: SEM spent garnet.

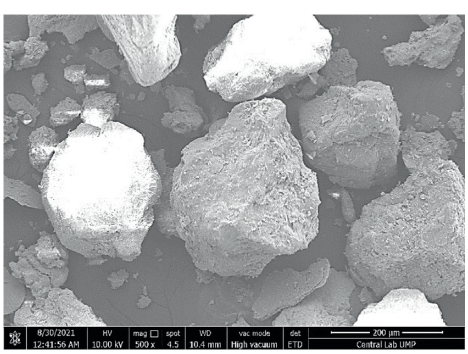


Figure 4: SEM river sand.

chunks (Figure 1) were initially crushed with the required size jaw crusher. Then, POC was sieved by passing 10 mm and retaining 5 mm to get the required size for replacement of coarse aggregate. Air-dried river sand was used as a fine aggregate with particle size passing of 2.36 mm and fineness modulus of 3.85. The spent garnet (Figure 2) was collected from a factory that provides integrated brownfield services for the oil and gas and petrochemical industries in West Malaysia. The waste was oven-dried at a temperature of

Table 4: Mix proportion used (kg/m^3).

Mixes (%)	Sand	Sg	POC	OPC	Water	SP
0	625	—	345	375	158	3.75
10	563	63	345	375	158	3.75
20	500	125	345	375	158	3.75
30	438	188	345	375	158	3.75
40	375	250	345	375	158	3.75

$105^{\circ}C \pm 5$ for 24 hours to remove the moisture content and sieved passing 600 μm. The physical properties of river sand and spent garnet are shown in Table 2, and the chemical composition of spent garnet is tabulated in Table 3. Figures 3 and 4 show the spent garnet and river sand's scanning electron image, respectively. Tap water was used for preparing the specimen for concrete and curing purposes. 1% superplasticizer from cement was used to produce workable mix while keeping low water cement ratio.

2.2. Mix Design and Preparation. The trial mix method was used to generate a total of five different palm oil clinker lightweight aggregate concrete mixes of grade 50. The percentages of spent garnet used to replace sand in the concrete mixes were 0%, 10%, 20%, 30%, and 40% by weight of fine aggregate. Each mix had the same quantity of cement, POC as coarse aggregate, water, and superplasticizer. The concrete mixture proportions used in this experiment are listed in Table 4. The lightweight concrete aggregate mix was prepared using a mechanical mixer. Sand, POC aggregate, spent garnet, and cement were dry-mixed for three minutes before adding water and superplasticizer. The remaining water and SP were mixed and put into the concrete mix, which was then mixed for 5 minutes. Concrete was cast in cubes and compacted appropriately. The concretes were covered with a damp gunny bag and kept in the mould for 24 hours before being removed. All concrete cubes were 7-, 28-, and 60-day water cured. The compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, water absorption, and acid resistance of the concrete were then determined.

2.3. Test Methods. The slump test was performed in accordance with BS EN 12350–2 [26] to establish the workability of the concrete mix. The dry density of the concrete specimen was determined according to ASTM C 642 [27]. The compressive strength of POC concrete was evaluated using the BS EN 12390–3 [28] standard testing procedure. For the flexural strength measurement, three-point bending tests were conducted according to BS EN 12390-5 [29]. Splitting tensile strength of the concrete cylinders was carried out by referring to ASTM C496-96 [30]. The static modulus elasticity of concrete was established by conducting testing in accordance with BS 1881: Part 121 [31]. The performance of concrete in terms of water absorption and acid resistance was evaluated through testing conducted following the procedure in BS EN 1881-122 [32] and experimental method of Sarıdemir et al. [33], respectively.

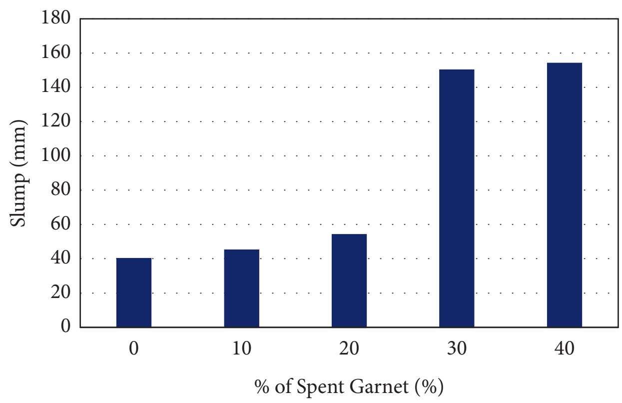


Figure 5: Slump value of POC LWAC containing spent garnet.

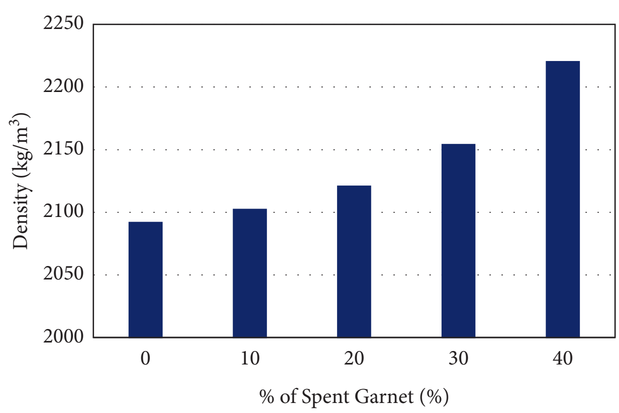


Figure 6: Oven dry density of POC LWAC containing spent garnet.

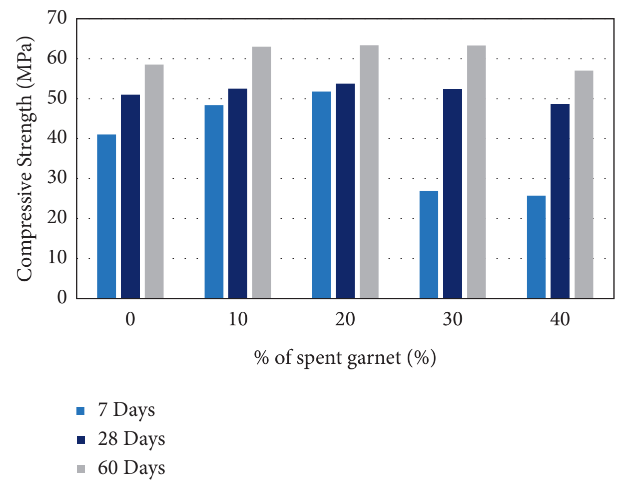


Figure 7: Compressive strength of POC LWAC containing spent garnet.

3. Results and Discussions

3.1. Workability. The effect of spent garnet as partial sand replacement in palm oil clinker lightweight aggregate concrete (POC LWAC) mixes towards slump is shown in Figure 5. As the spent garnet content was increased, the workability of POC LWAC increased. Figure 5 reveals slump values of 40 mm, 45 mm, 54 mm, 150 mm, and 154 mm for POC LWAC, with addition of 0%, 10%, 20%, 30%, and 40% of spent garnet, respectively. Control POC LWAC mixture was the least cohesive among the mixtures consisting of spent garnet. The improvement in the workability of the mix was due to the higher density of spent garnet (2006 kg/m^3) compared to river sand (1541 kg/m^3). The approach of integrating spent garnet to replace sand by weight resulted in smaller volume of this solid waste to be added to the mix, thus resulting in a mixture with enhanced workability. Furthermore, the smaller particle size of spent garnet improved the workability of concrete as the surface bonding between particles increased. A similar trend was also observed by the previous researchers [12, 34, 35] in different types of concrete.

3.2. Oven dry Density. Figure 6 shows that the inclusion of spent garnet increased the density of all mixes. Density of POC LWAC increased from 2091 kg/m^3, 2102 kg/m^3, 2120 kg/m^3, and 2154 kg/m^3 to 2220 kg/m^3 when the replacement levels of river sand by spent garnets were increased from 0% to 10%, 20%, 30%, and 40%, respectively. POC LWAC containing 40% of spent garnet exhibited the largest density value. This occurred because the spent garnet had higher bulk density and specific gravity compared to river sand, which were 2006 kg/m^3 and 3.75, respectively. The effect of using iron ore, which was a waste material with different bulk density, as fine aggregate on density of concrete has also been documented by the previous researchers [12, 35]. According to BS EN 1992-1-1 (2004) [36], lightweight concrete had density not more than 2200 kg/m^3. Therefore, all replacements were categorized as lightweight concrete excluded 40%.

3.3. Compressive Strength. The compressive strength of POC LWAC with varying percentages of spent garnet as a partial sand replacement is shown in Figure 7. Compressive strength increased steadily over time as the age increased. On Day 60 of curing age, the results indicated that the strength of POC LWAC containing 20% (63.4 MPa) spent garnet was the highest compared to the control specimen (58.6 MPa). The strength decreased as the percentage of spent garnets increased, reaching 63.3 MPa and 57.0 MPa at 30% and 40%, respectively. The mix with 20% of spent garnet demonstrated the highest strength value. The presence of finer aggregates in the particle size passing 600 μm filled in the existing spaces in the concrete, thus forming more compact concrete structure with higher strength. The increase in compressive strength of POC LWAC could partly be attributed to spent garnets' rough and angular texture, and finer particles. According to Muttashar et al. [16], the coarse and angular texture of the spent garnet materials increased bonding at the cement-aggregate contact, resulting in the high strength. The study also stated that a rough and angular surface on the materials improved the grip between the particles and reduced the strength loss that led to higher strength of the concrete [37]. In addition, lower water absorption of spent garnet means fewer pores on the concrete surface and a stronger bond between cement paste and aggregates [38]. The difference in the internal structure fashion was due to the use of suitable spent garnet content that can be seen in Figures 8 and 9. The microstructure of control specimen is less compact, as illustrated in Figure 8, in contrast to the concrete with 20% spent garnet, which appears well-packed and denser, as in Figure 9. Precaution needed to be taken to not use this waste excessively as the use of spent garnet at 30% and 40% decreases the compressive strength of concrete. However, the mix produced using 30% can still be classified as high strength concrete, whereas the one produced by integrating 40% spent garnet can be used for structural application.

The relationship between compressive strength against spent garnet content and curing days is presented in Figure 10. As suggested from response surface method (RSM), the quadratic model was the best fit to maximize the relationship. The plot shows that the compressive strength improved with prolonged curing days. However, it was obvious that the compressive strength decreased with an increase in the level percentage of spent garnet in POC LWAC, as shown in Figure 10(a). The RSM plots also clearly displayed that inclusion of 20% spent garnet in POC LWAC enhanced the strength performance as compared to plain POC LWAC and those contained 10%, 30%, and 40% spent garnet. The analysis is fit from 0, 10, 20, 30, and 40%, in which the regression analysis (from ANOVA analysis) is approaching to value $R^2 > 0.80$. The strong relation proves the effectiveness of the spent garnet as 20% of replacement towards compressive strength. Figure 10(b) depicts a graphic representation of response surface to visualize the effects. A curvature in the plot indicates the sensitivity of response factors. The curvature of Curve A was more curved than that of Curve B, thus indicating that those different levels of percentages spent garnet were more sensitive than the age of curing to enhance the compressive strength. From ANOVA analysis, the regression indicated that the relationship between compressive strength and those variables was strong, where R^2 value was 0.866. The empirical relationship between compressive strength and multiples factors (% spent garnet and curing days) is presented in the following equation:

$$\mathrm{CS} = -0.0191\mathrm{A}^2 - 0.0060\mathrm{B}^2 + 0.0086\mathrm{AB} + 0.291\mathrm{A} + 0.652\mathrm{B} + 38.902, \tag{1}$$

where CS is compressive strength, A is percentage of spent garnet, and B is curing day.

3.4. Flexural Strength. The results of flexural strengths of POC LWAC containing spent garnet are shown in Figure 11, which illustrates strength at Day 7, Day 28, and Day 60 of concrete age. The flexural strengths of 4.21 MPa, 8.13 MPa, 8.45 MPa, 7.92 MPa, and 7.74 MPa at the age of Day 7 in mixtures of 0%, 10%, 20%, 30%, and 40%. However, at Day 28 and Day 60 of curing age, the flexural strengths of the specimens were 10.98 MPa, 11.09 MPa, 11.10 MPa, 10.95 MPa, 10.66 MPa, and 11.21 MPa,

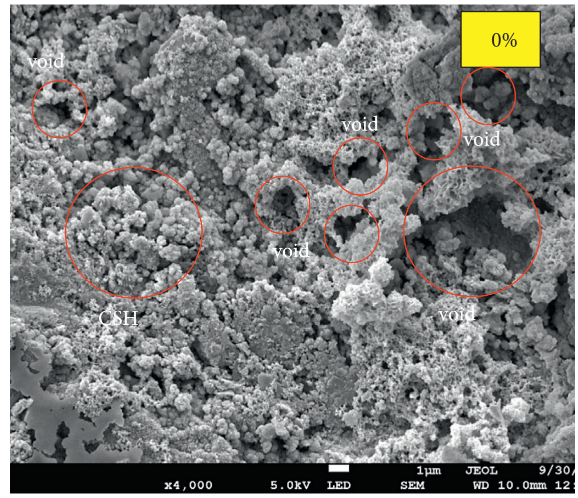


Figure 8: POC control specimen with many voids.

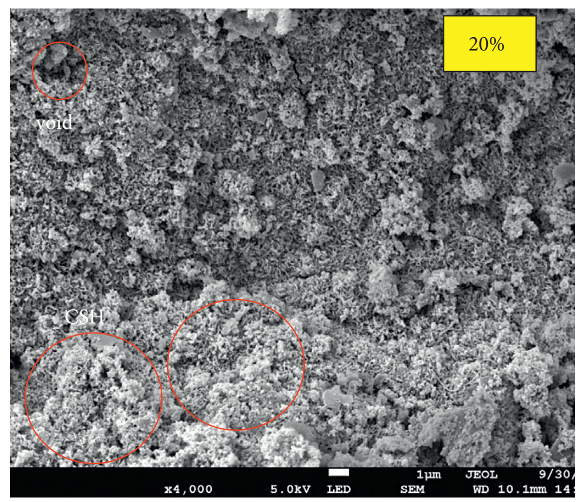


Figure 9: Specimen containing 20% spent garnet with lesser amount of voids.

11.22 MPa, 11.46 MPa, 11.21 MPa, and 11.20 MPa, respectively. Evidently, all specimens demonstrated strength increment as the curing period became longer, resulting from better hydration process. The test results revealed that POC LWAC containing spent garnet in 20% enhanced strength compared to the control POC LWAC at all ages. However, the mixture produced using 30% and 40% replacement of spent garnet showed a decrease in flexural strength, whereby the pattern was similar to the compressive strength result. SOman et al. [39] and Kim and Lee [40] also described similar observations upon the use of high amount of waste material as sand replacement in concrete.

The response surface 3D plot in Figure 12 indicates the relationship between percentage of spent garnet and curing day towards flexural strength. It was found that POC containing higher content of spent garnet had no effect on the flexural strength when compared to plain POC specimens. The plots in Figure 12(a) clearly illustrate that POC incorporating 20% spent garnet attained the highest

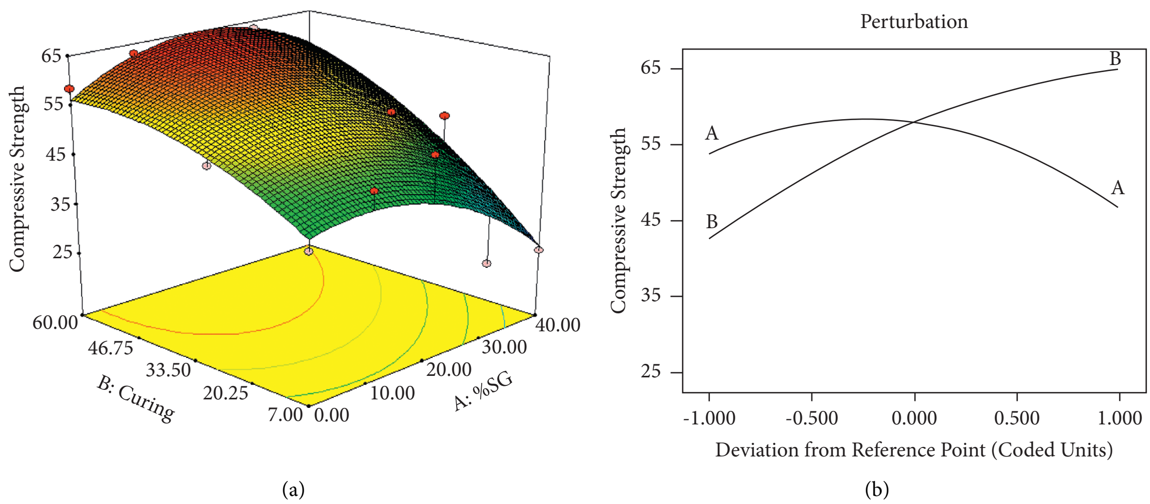


FIGURE 10: Response surface plots (a) and perturbation plots (b) indicating the relationship between spent garnet content and curing days with respect to compressive strength.

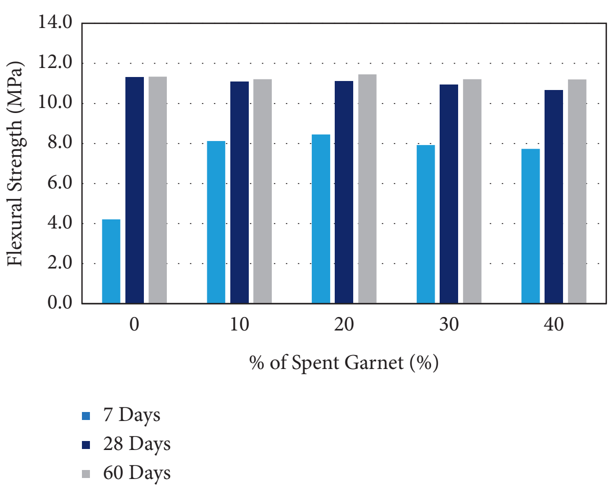


FIGURE 11: Flexural strength of POC LWAC containing spent garnet.

flexural strength as compared to that plain POC. By using ANOVA analysis, the regression indicated that the effect of different level percentage of spent garnet and curing days towards flexural strength was significant. The quadratic model was selected, and the value of R2 obtained from the analysis was 0.9939. Overall, the analysis is fitting from 0, 10, 20, 30, and 40% as the regression analysis (from ANOVA analysis) is approaching value > 0.80. Thus, the robust relation demonstrates the efficacy of the spent garnet at 20% replacement towards flexural strength of concrete. It is interesting to note that Figure 12(b) demonstrates that Curve B was much curved than Curve A, thus indicating that prolonging the curing day was more sensitive than the content of spent garnet to enhance the flexural strength. From the quadratic regression, the relation equation between spent garnet content and curing day on flexural strength of spent garnet based POC is shown in the following equation:

$$FS = -0.0002A^2 - 0.0024B^2 + 0.0003AB - 0.013A + 0.215B + 7.126, \tag{2}$$

where FS is flexural strength, A is percentage of spent garnet, and B is curing day.

3.5. Splitting Tensile Strength. Figure 13 illustrates the effect of substituting spent garnet for sand on the splitting tensile strength of POC LWAC. The splitting tensile strength of POC LWAC mixes containing 20% spent garnet waste was greater than that of the control sample at all curing ages. This might be because the optimal proportion of finer garnet particles resulted in improved bonding between aggregates and cement paste. Utilizing spent garnet more than 20% resulted in a weaker concrete with a lower splitting tensile strength. The decreased fine aggregate ratio was ascribed to the deterioration of interface between the spent garnet particles and binder paste. Huseien et al. [12] previously observed a decline in concrete strength because of excessive waste material use.

Figure 14 evaluates the relationship between spent garnet content and curing days against splitting tensile strength. The quadratic model was designed by RSM to obtain the best fit for splitting tensile strength relation with the percentage of spent garnet and curing days, as presented in Figure 14(a). The results described that the splitting tensile strength for POC was influenced by the inclusion of spent garnet in POC mixes. Based on the regression analysis (from ANOVA analysis), which is approaching (value $R^2 > 0.80$), it can be deduced that the analysis is fit from 0, 10, 20, 30, and 40% of spent garnet as fine aggregate replacement. The 3D surface response showed that when the content of spent garnet increased, the splitting tensile strength of POC specimens decreased. In contrast, when the curing days increased, the splitting tensile strength increased with decreasing spent garnet content. The quadratic regression analysis revealed that R^2 obtained was 0.9861, which means that about 98.61% of its

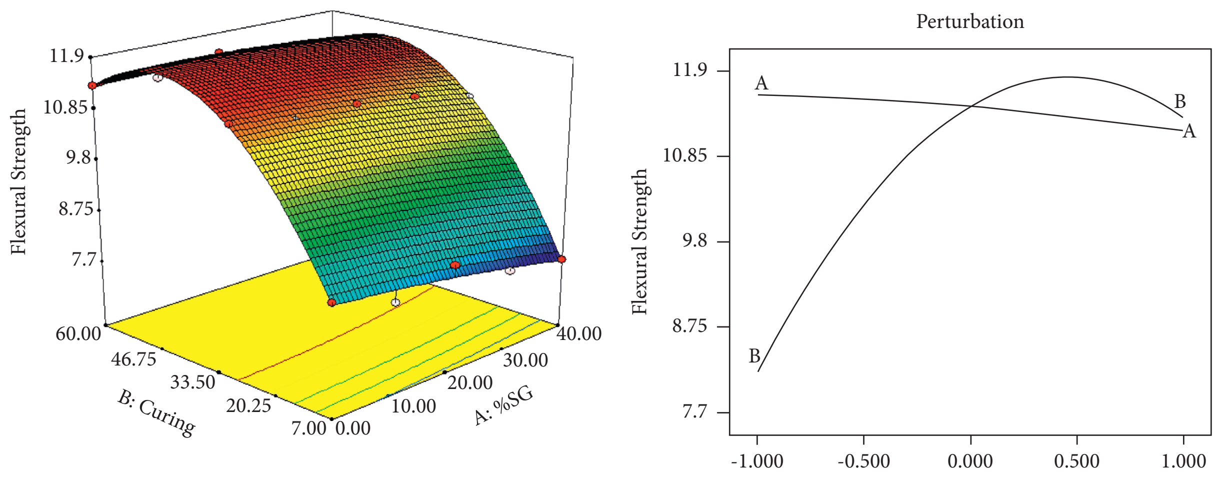


Figure 12: Response surface plots (a) and perturbation plots (b) indicating the relationship between spent garnet content and curing days with respect to flexural strength.

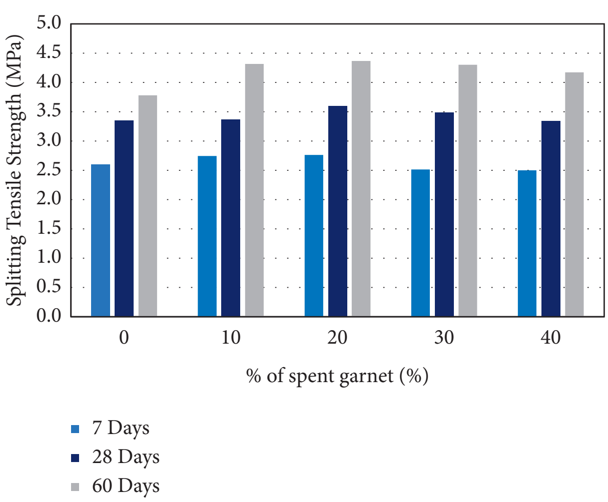


Figure 13: Splitting tensile strength of POC LWAC containing spent garnet.

spent garnet content and curing days contributed to the variation in splitting tensile strength of POC. Instead, the adequacy of the model was also tested by examining the perturbation trends, as depicted in Figure 14(b). The steep slope in the perturbation plots shown in Curve A for the content of spent garnet indicated that the inclusion of different percentages of spent garnet in POC enhanced the strength properties. The relation equation between splitting tensile strength with respect to that spent garnet content and curing days is shown in the following equation:

$$TS = -0.0006A^2 - 0.0003B^2 + 0.0002AB + 0.04A + 0.02B + 2.29, \quad (3)$$

where TS is splitting tensile strength, A is percentage of spent garnet, and B is curing day.

3.6. Modulus of Elasticity. The results of modulus of elasticity at age of 7, 28, and 60-day curing are shown in Figure 15. It can be observed that the variation in the amount of spent garnet used influenced the stiffness of the POC LWAC. The combination of 20% spent garnet as fine aggregate increased the modulus of elasticity by 32%, 59%, and 7.02%, respectively, compared to control mixture at all ages. The positive contribution of 20% spent garnet inclusion to form denser internal structure resulted in the formation of lower deflection of concrete upon subjected to loading. According to Neville [38], an increase in the modulus of elasticity of concrete signified an increase in the stiffness of the concrete element, which may result in less deflection in the structural element. Similar patterns were seen in the compressive strength result obtained in this study. The elastic modulus of concrete was usually directly proportional to its compressive strength (high strength constitutes high elastic modulus) [41]. Upon inclusion of 30 and 40% of spent garnet in the mix, concrete became less stiff and exhibited lower modulus elasticity value.

The effect of numerical factors between spent garnet content and curing days towards modulus of elasticity (MOE) of POC and POC contained spent garnet was found by RSM analysis and presented in Figure 16. In this RSM analysis, the 3D surface response plots displayed that the inclusion of spent garnet in POC mixes significantly affected MOE, as shown in Figure 16(a). POC with 20% spent garnet resulted in higher MOE as compared to those of POC mixes. The 3D surface response plots also demonstrated that when the duration of curing prolonged, MOE also increased. It was observed that the spent garnet content and curing days had a strong relationship with the MOE (R^2 was 0.8486). It can be stated that the different percentages of spent garnet in POC mix were more dominant in prescribing the MOE of concrete. The perturbation plots were drawn to estimate the influence of individual effect of those variables to the MOE of POC and are presented in Figure 16(b). It demonstrates

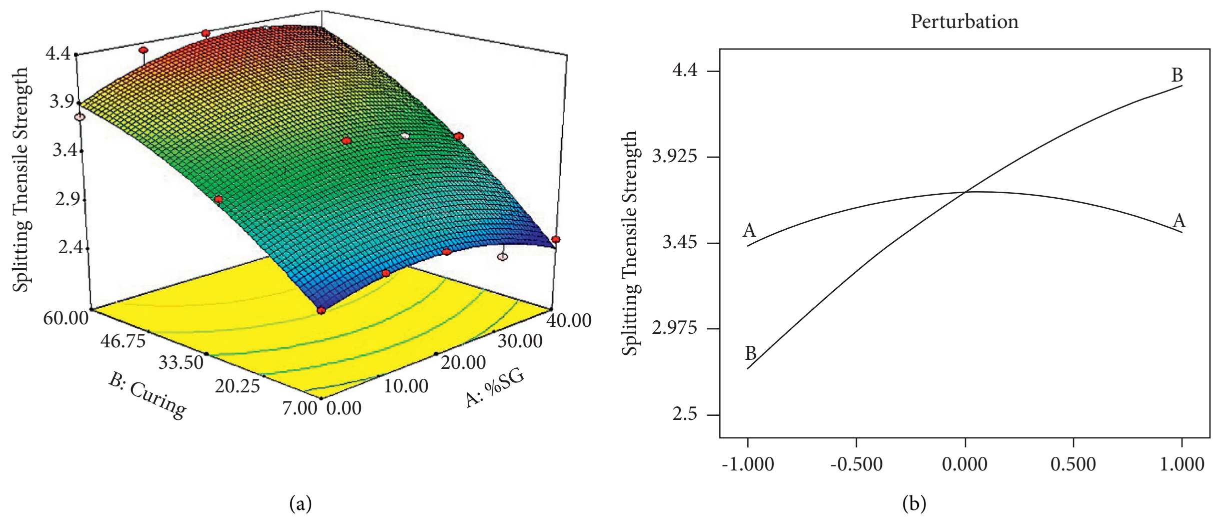


FIGURE 14: Response surface plots (a) and perturbation plots (b) indicating the relationship between spent garnet content and curing days with respect to splitting tensile strength.

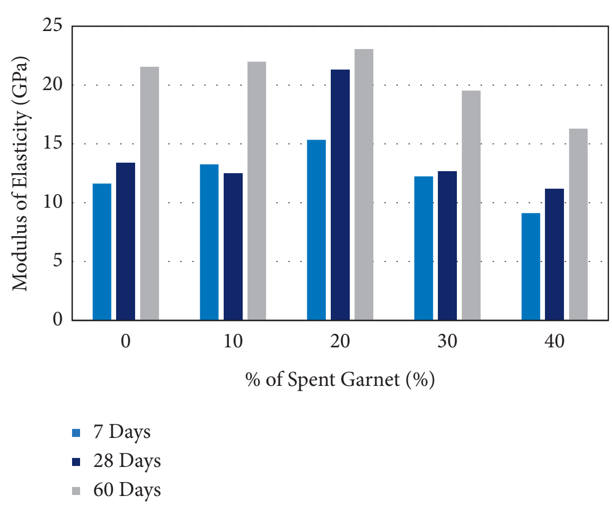


FIGURE 15: Modulus of elasticity of POC LWAC containing spent garnet.

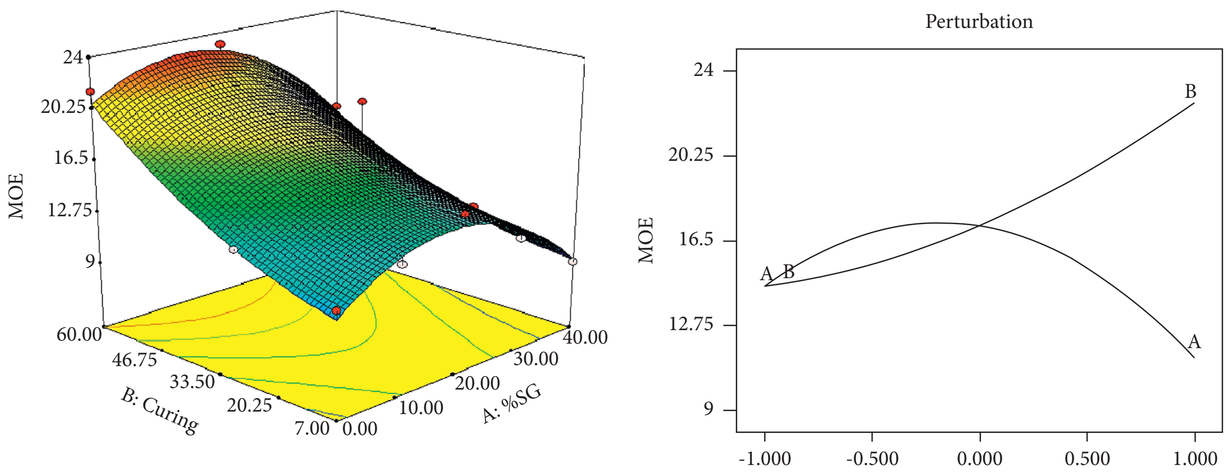
that Curve A (spent garnet content) showed more curvy nature as compared to Curve B (curing days). Therefore, Curve A shows that response was sensitive, indicating that increment in MOE of POC decreased the content of spent garnet in POC mixes. The empirical relationship between compressive strength and multiples factors (% spent garnet and curing days) is expressed in Equation (4). It is observed that there is a potential relationship between the compressive strength and its modulus of elasticity with an adjustment around $R^2 = 0.54$ as shown in Figure 17.

$$MOE = -0.0108A^2 + 0.0020B^2 - 0.0014AB + 0.398A + 0.049B + 10.568, \tag{4}$$

where MOE is modulus of elasticity, A is percentage of spent garnet, and B is curing day.

3.7. Water Absorption. The effect of spent garnet as a partial fine aggregate replacement on the water absorption of POC LWAC is shown in Figure 18. According to the 28-day results, water absorption was 2.8%, 2.7%, 2.0%, 2.5%, and 2.6% for 0%, 10%, 20%, 30%, and 40% replacement of spent garnet in POC concrete, respectively. All POC LWAC specimens were categorized as good quality concrete as the water absorption was less than 4%. According to Neville [38], concrete with water absorption of less than 10% is classified as good quality concrete. The integration of 20% spent garnet, which resulted in the lowest water absorption value than other replacements, could be associated with the spent garnet fine particles acting as filler, thus forming a more compact structure. Figure 19 proves that concrete with 0% spent garnet had more void and less density, resulting in the highest water absorption compared with mix formed using 20% of spent garnet replacement, as shown in Figure 20. According to Zhang et al. [37], the decrease in water absorption was mostly due to the inner structure gradually densifying. However, excessive use of spent garnet at 30% and 40% caused rise in water absorption value. When too much of spent garnet was used, the packing level of aggregate may be inadequate, resulting in voids inside the concrete specimens. These unfilled voids allowed water to infiltrate and fill the voids. Therefore, a 20% replacement of sand with spent garnet was regarded as optimum and created the best specimen of all. Figure 21 show that water absorption has no clear relationship with compressive strength.

3.8. Acid Resistance. As illustrated in Figure 22, the usage of spent garnet affects the durability of POC LWAC that has been immersed in a 10% hydrochloric acid solution for 28 and 60 days, respectively. Generally, as the immersion duration increased, all concrete specimens undergo higher mass loss and strength. Figure 23POC LWAC containing up to 30% of spent garnet exhibit lower mass loss and strength



(a) (b)

Figure 16: Response surface plots (a) and perturbation plots (b) indicating the relationship between spent garnet content and curing days with respect to modulus of elasticity (MOE).

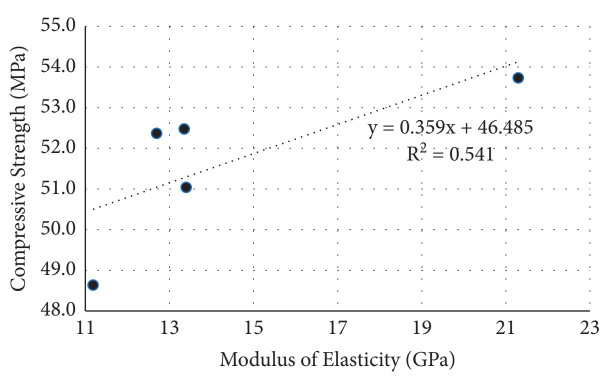


Figure 17: Fitted line plots of regression analysis for the relationship between compressive strength and modulus of elasticity on 28-day curing.

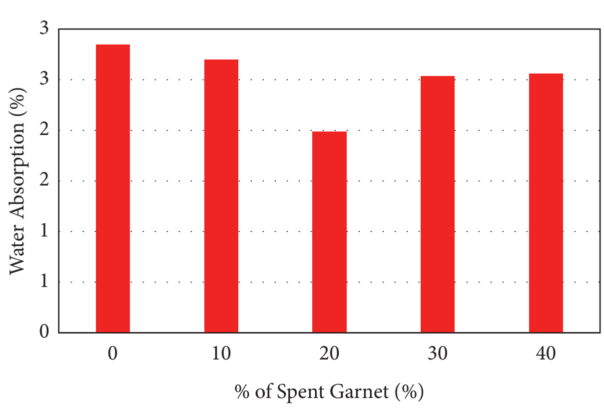


Figure 18: Water absorption of POC LWAC containing spent garnet.

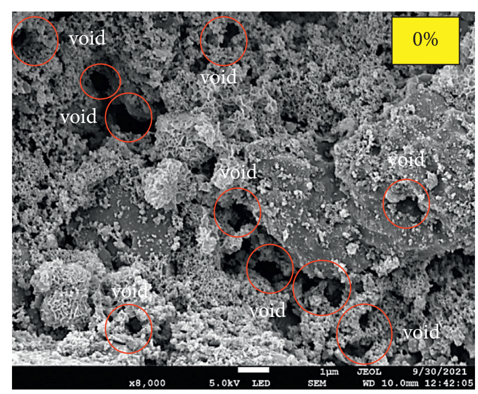


Figure 19: Appearance of many voids in the POC LWAC specimens containing 0% spent garnet.

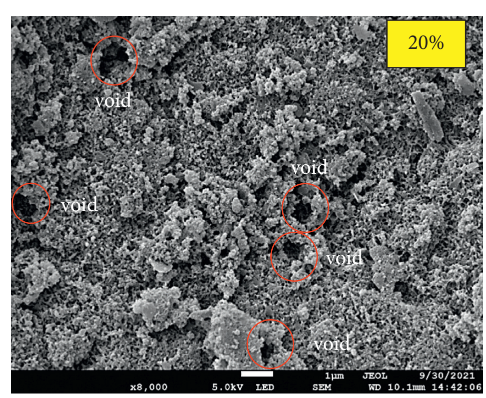


Figure 20: Appearance of lesser void in the POC LWAC specimens containing 20% spent garnet.

reduction as compared to plain concrete. The mix produced using 20% spent garnet demonstrates the least mass loss and strength reduction across the various immersion durations compared to other specimens. After 60 days of hydrochloric acid, the mass loss and strength reduction of 20% spent garnet are 0.57% and 10.8%, respectively, compared to the control specimen, 1% and 19.3%, respectively. The ability of POC LWAC sample with 20% of spent garnet replacement to withstand the acidic attack is related to the filler effect

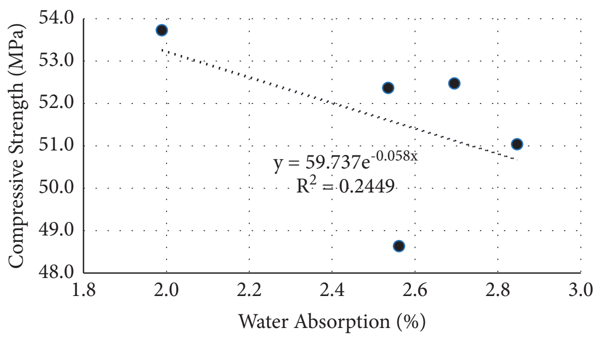


Figure 21: Fitted line plots of regression analysis for the relationship between compressive strength and water absorption.

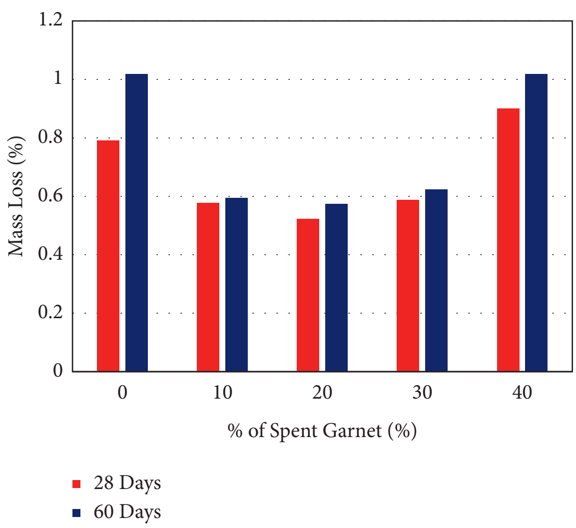


Figure 22: Mass loss of POC LWAC due to acid attack.

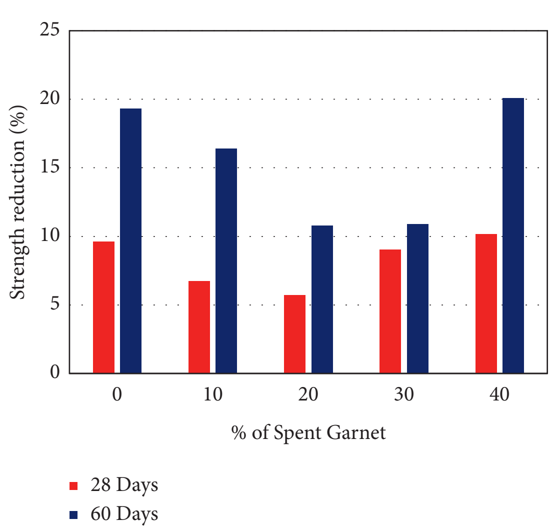


Figure 23: Strength reduction of POC LWAC due to acid attack.

provided by the spent garnet, which contributed to the densification concrete by reducing the voids. This condition makes the durability of POC LWAC with 20% of spent garnet in acidic environment is higher compared to control

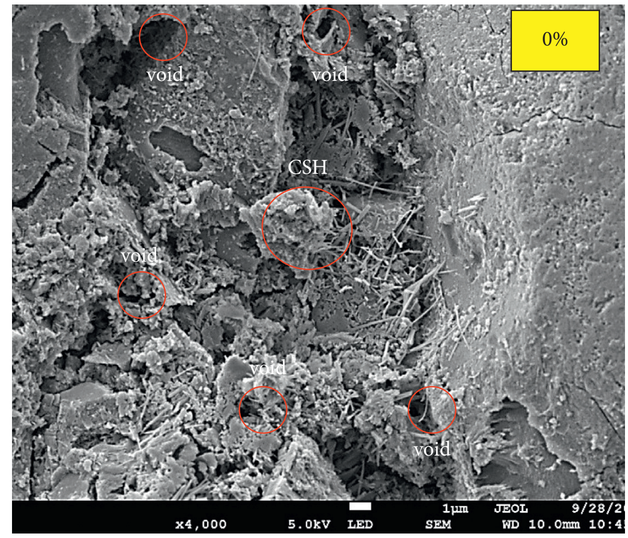


Figure 24: Microstructure of POC LWAC containing 0% spent garnet after exposure to hydrochloric solution at 28 days.

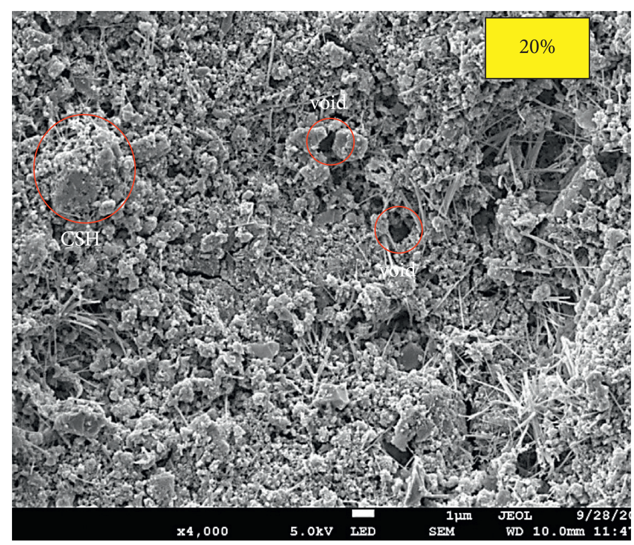


Figure 25: Microstructure of POC LWAC containing 20% spent garnet after exposure to hydrochloric solution at 28 days.

specimen. The scanning electron microscope image of the samples after acid resistance test shows control specimen (Figure 24) with the surface texture that has been exposed to leaching and the presence of large voids in contrast to mix with 20% spent garnet (Figure 25) with lesser voids. Zivica and Bajza [43] stated that the acidic resistance of cement-based materials is significantly dependent on pore size distribution. The resistance of the concrete was increased when its content of finer pores decreased. Extreme use of spent garnet of 40% significantly reduces the durability of concrete to acid attack. Due to the hydrochloric acid attack, the concrete matrix weakened, and the specimen's weight decreased due to the loss of cement paste. Calcium hydroxide is soluble in water and tends to get leached out from the concrete surface upon exposure to acidic environment. Conclusively, inclusion of 20% spent garnet improved the

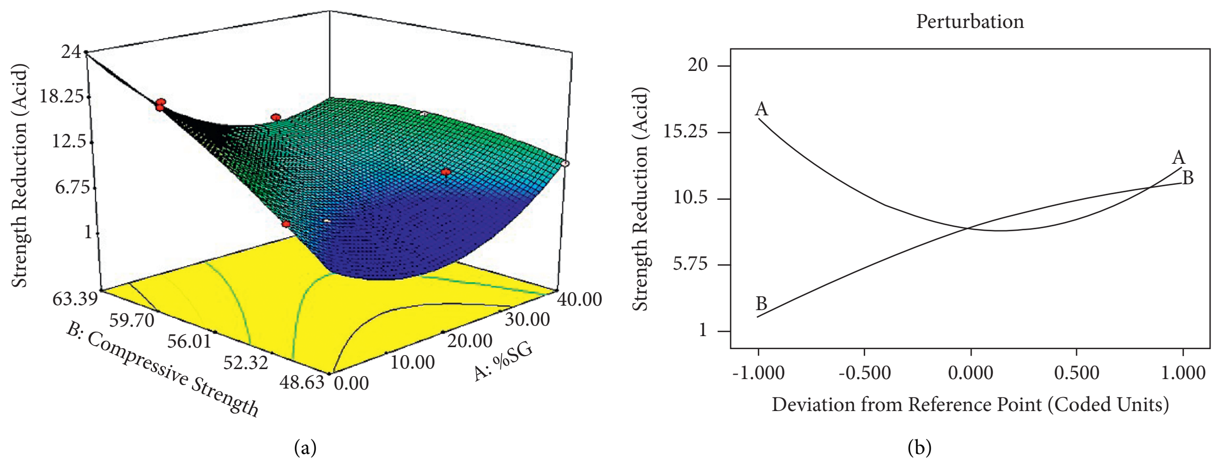


Figure 26: Response surface plots (a) and perturbation plots (b) indicating the relationship between spent garnet content and strength reduction with respect to strength reduction (acid resistance).

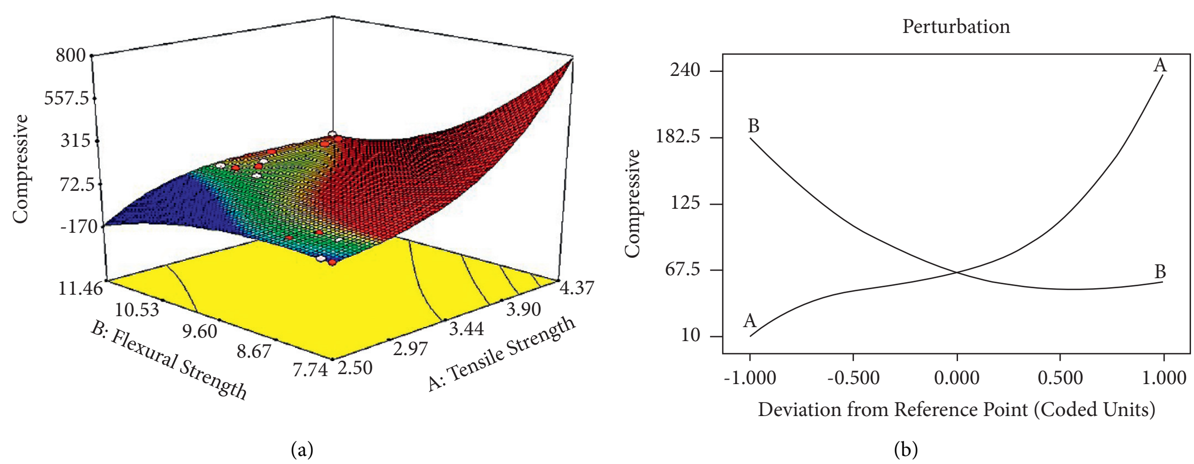


Figure 27: Response surface plots (a) and perturbation plots (b) indicating the relationship between compressive, flexural, and splitting tensile strength.

internal microstructure of the concrete by filling internal spaces and resistance to acid attack.

The verification was performed to confirm the effect of spent garnet in POC LWAC to acid resistance, as shown in Figure 26. The RSM plots indicated the relationship between spent garnet content and compressive strength towards strength reduction when the POC LWAC specimens were immersed in acid solution at Day 28 and Day 60. The 3D surface plots in Figure 26(a) illustrate that the spent garnet and compressive strength of plain POC specimens and a series of spent garnet-based POC specimens significantly affected the strength reduction. It can be noted that when the spent garnet content was increased, the compressive strength of POC LWAC decreased consequently, influencing the reduction in strength. Figure 26(b) shows the perturbation plots to compare the individual effect (% spent garnet and compressive strength) on the strength reduction (acid resistance). It shows that, with the curvature in the levels of percentage spent garnet, Curve A seemed to be much curved than Curve B, indicating that Curve A was more sensitive to the strength reduction. Therefore, POC LWAC containing 20% spent garnet provided positive effect. Inclusion of 20% spent garnet in POC LWAC exhibited an increase in strength and good resistance when exposed to acid solution. The quadratic model was the best fit for the analysis, and the value of R^2 obtained was found to be 0.961. R^2 obtained showed strong correlation for the model. This means that about 96.10% variation in the strength reduction could be explained by the spent garnet content in POC concrete.

4. Relationship between Compressive, Flexural, and Splitting Tensile Strength

Figure 27 illustrates the relationship between compressive, flexural, and splitting tensile strength of the POC LWAC containing spent garnet. As suggested from the response surface method (RSM), the cubic model was the best fit to maximize the relationship. The results described that the compressive strength for POC LWAC was influenced by flexural strength. It can be observed from the regression model that a strong relation was existing in between compressive, flexural, and splitting tensile strength having R^2

greater than 90%. Figure 27(b) shows the perturbation plots to compare the individual effect (flexural strength and splitting tensile strength) on the compressive strength. It shows that the curvature in levels of flexural strength Curve B seemed to be much more curved than Curve A, indicating that Curve B was more sensitive to the compressive strength.

5. Conclusion

The following conclusions can be drawn from this investigation:

(1) POC concrete mixes had a slump value in the range of 40 mm–185 mm. As the spent garnet content increased, the workability of concrete increased.

(2) The density of POC concrete increased with the increase of spent garnet in the concrete mix. It ranged from 2091 kg/m^3 to 2220 kg/m^3 because the bulk density of spent garnet was higher than that of river sands.

(3) The highest compressive strength was 63.4 MPa with spent garnet replacing 20% of the sand. At Day 60 of water curing, the lowest compressive strength recorded was 57 MPa with 40% replacement of spent garnet as sand.

(4) The flexural strength, splitting tensile strength, and modulus of elasticity of concrete mixtures prepared with 20% spent garnet were higher than those of the corresponding control concrete.

(5) By substituting 20% spent garnets for river sand, the durability properties such as water absorption and resistance to hydrochloric acid attack were enhanced.

(6) The viability of integrating spent garnet as an acceptable substitute for river sand in POC concrete was demonstrated in this research.

(7) The response surface plots clearly displayed that the inclusion of 20% spent garnet in POC mix enhanced the performance of spent garnet based POC. The regression coefficient (R^2) derived from the ANOVA analysis also indicated that the relationship between factors and those variables is strong. The robust relation verifies the effectiveness of 20% spent garnet as partial fine aggregate replacement towards compressive strength, flexural strength, and splitting tensile strength. The prediction model can be used as reference model for future testing on spent garnet in POC concrete. [42].

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors state that they have no known conflicting financial or personal interests that might seem to have influenced the work presented in this study.

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