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Mechanical Performance of Concrete Incorporating Wastewater Treatment Sludge from Pet Bottle Washing Recycling Lines as Partial Cement Replacement

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Abstract

This study focused on the effect of using wastewater treatment sludge from polyethylene terephthalate (PET) bottle washing recycling lines (PWLS) as a partial cement replacement in concrete production. The concrete was produced with a constant mix proportion by controlling the water-to-cement ratio and aggregate content. Thus, in this study, a total of 16 mix designs were produced using PWLS as a partial cement replacement of 1% and 5% of the cement mass, with water-to-cement ratios of 0.55 kg and 0.65 kg, and curing periods of 7 and 28 days. Slump tests were conducted to determine the fresh concrete workability, while density, water absorption, and compressive strength tests were conducted at 7 and 28 days after curing periods. As for the chemical composition characterization of PWLS, X-ray fluorescence (XRF) analysis was conducted. Design Expert software is being used to conduct a statistical analysis through analysis of variance (ANOVA) and numerical optimization. The incorporation of 1% PWLS as partial cement replacement achieved the highest mechanical properties, with a compressive strength value of 37.9 MPa at 7 days and a predicted value of 31.1 MPa at 28 days, while density of 1993.75 kg/m^3, and water absorption of 2.126% with a desirability of 0.853. Hence, the key finding of this study showed that the PWLS contain 82.9% aluminum, iron, and silicon oxides, which confirm its suitability as a supplementary cementitious material. Therefore, the incorporation of 1% PWLS has achieved the optimum balance between mechanical performance and sustainable waste utilization, while 5% replacement significantly reduced its strength due to delayed hydration.

1. Introduction

Concrete is widely used in construction due to its versatility and cost-effectiveness. It is traditionally composed of cement, water, aggregates and remains fundamental to the development of buildings, infrastructure, and structural components. However, the production of cement is highly energy-intensive and contributes significantly to global carbon dioxide CO_2 emissions, thereby raising serious environmental sustainability concerns [1]. As environmental concerns increase, the construction industry faces higher pressure to adopt sustainable and low-carbon alternatives to partially replace cement in concrete applications.

Various types of sludge have been investigated as partial cement replacements in concrete to mitigate environmental impacts and enhance sustainability in the construction sector. These include the water supply plant sludge [2] hypo sludge [3], alum sludge [4], waste water sludge [5], [6], paper industry waste sludge, [7] and polysilicon sludge [8]. The utilisation of such sludge materials in concrete is primarily motivated by their potential to reduce cement consumption, divert waste from landfilling, and lower the overall carbon footprint of construction materials.

Meanwhile, PET plastic recycling washwater typically generate wastewater with high chemical oxygen demand (COD) and biochemical oxygen demand (BOD), as well as elevated concentrations of total suspended solids (TSS), fats, oils, and grease. If not properly managed, PWLS presents significant disposal challenges and potential environmental risks, particularly due to its high moisture content, residual organic matter, and limited reuse options. The potential application of this sludge as a construction material resource remains underexplored due to its complex and heterogeneous composition of this sludge creates uncertainty about its mechanical and durability performance, including compressive strength, density, and water absorption when it is incorporated into concrete. Additionally, there are currently no established guidelines or standardised methodologies to determine the optimal replacement level of the PET washing line sludge that can be added to concrete, as a replacement for cement, without compromising either the structure or long-term performance [1].

The following are the objectives of this study:

- To characterize and assess the suitability of PWLS as a potential cement replacement.
- To evaluate the effects of PWLS on the properties of concrete, specifically density, water absorption, and compressive strength.
- To determine the optimal percentage of PWLS using a factorial design approach for performance maximization.

2. Materials and Method

The materials used in this experimental study include Ordinary Portland Cement (OPC) as the primary binder, river sand as fine aggregate, crushed stone as coarse aggregate, clean potable water, and PET washing line sludge (PWLS) as a partial replacement for cement. The PWLS was sourced from an industrial PET bottle recycling facility and used at replacement levels of 1% and 5% by weight of cement. All materials were mixed according to MS 523:2008 standards and tested for compressive strength, density, and water absorption of the concrete cubes.

2.1 Cement

This study utilized Ordinary Portland Cement (OPC) as the primary binding material. OPC is a type of hydraulic cement that undergoes a chemical reaction with water, forming a hardened paste that effectively binds aggregate particles. OPC complies with Malaysian Standard MS EN197-1 and was stored in a sealed, moisture-proof container to avoid any potential loss in quality due to water absorption or premature hydration [9]. Before mixing, the cement was sieved through a mesh with an opening of 150 microns to remove impurities and agglomeration, ensuring uniform mixing and proper activation [10], [11], [12].

2.2 Fine Aggregate

Natural river sand was utilized as the fine aggregate in this study. Sourced from a local supplier, the sand was sieved to ensure it passed through a 4.75 mm sieve in accordance with standard specifications. The sand was washed to remove impurities and checked for grading, moisture content, and specific gravity to ensure proper mix proportions. The sand used complied with MS EN 12620 standards and was free from impurities such as clay and organic matter.

2.3 Coarse Aggregate

This study utilized crushed granite stones with a passing size of 20 mm as coarse aggregate. The aggregates are washed to remove all impurities and checked for grading, moisture content, and specific gravity to ensure a proper mix proportions. Coarse aggregate is crucial in providing the concrete mix with strength, bulk, and load-bearing capacity. Hence, the chosen aggregate size was suitable to produce concrete cubes, ensuring the proper compaction and effective mechanical performance.

2.4 Water

Portable water was used for both mixing and curing phases of concrete specimens. The water was measured accurately according to the water-to-cement ratio that had been specified in the JKR standard [13]. This was to ensure that the concrete had a proper hydration and workability. For curing, the concrete cubes were immersed in a water tank for 7 to 28 days to maintain their moisture, allowing the concrete to mix well with the PWLS. This was done to achieve optimal strength.

2.5 X-Ray Fluorescence (XRF) Analysis

PWLS was analyzed using X-ray Fluorescence (XRF) spectroscopy to determine its chemical composition. A sample of dried PWLS, ground into a fine powder, was prepared and analyzed using standard laboratory procedures for XRF analysis [14]. The analysis also provided the Major Oxide Components (MOC) and other elemental content of PWLS where, it is offered insight into its suitability as a partial cement replacement. XRF data serves as a supplement to mechanical and physical testing results, providing a more comprehensive assessment of the PWLS material without altering any of the mix design or testing procedures.

2.6 PET Washing Line Sludge (PWLS)

PWLS was collected from local PET washing line wastewater treatment facilities, where the sludge was treated as industrial waste. The sludge was collected according to the best practice waste collection method [15]. It was also be in accordance with standard procedures for incorporating waste materials into concrete [16]. After the collection, the PWLS was air-dried under direct sunlight or oven-dried at 105 °C temperature for about 24 -48 hours to reduce the moisture content below 10% and to stabilize the material. This was done to prevent degradation due to biological or chemical reactions [17]. Thus, once the PWLS sludge has dried, it was processed using a mechanical grinder to achieve a fine particle size (150 μm). This was to ensure that any larger or fibrous material was removed to ensure its uniformity. The prepared PWLS undergoes quality assessment using standard laboratory methods, including particle size distribution, moisture content, and chemical composition tests.

2.7 Mix Proportions

The concrete mix proportions in this study aimed to produce normal-strength concrete, targeting a characteristic compressive strength of 30 MPa at 28 days using PWLS replacement at 1% and 5% by weight of cement. All of the mixtures used the same water-to-cement ratio and aggregates amount to ensures a consistent level of workability and hydration, while keeping the aggregate contents the same, removing any additional influences on the compressive strength, density, and water absorption performance of the concrete mixture. Therefore, the effect of the PWLS can be compared directly. PWLS replace cement by weight at levels of 1% and 5%. Table 1 shows the concrete mix proportions.

Table 1 *Concrete mix proportions*

Mix Id	PWLS (%)	Cement/PWLS (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)	Water-to-cement Ratio (kg)
CM	0	1.06/0.00	2.04	3.62	0.57
M1	5	1.00/0.06	2.04	3.62	0.55
M2	5	1.00/0.06	2.04	3.62	0.65
M3	5	1.00/0.06	2.04	3.62	0.55
M4	1	1.05/0.01	2.04	3.62	0.55
M5	1	1.05/0.01	2.04	3.62	0.65
M6	5	1.00/0.06	2.04	3.62	0.55
M7	1	1.05/001	2.04	3.62	0.55
M8	1	1.05/0.01	2.04	3.62	0.65
M9	1	1.00/0.06	2.04	3.62	0.65
M10	1	1.05/0.01	2.04	3.62	0.65
M11	5	1.00/0.06	2.04	3.62	0.55
M12	5	1.00/0.06	2.04	3.62	0.65
M13	1	1.05/0.01	2.04	3.62	0.65
M14	5	1.00/0.06	2.04	3.62	0.65
M15	1	1.05/0.01	2.04	3.62	0.55
M16	5	1.00/0.06	2.04	3.62	0.55

2.8 Design of Experiment

A two-level factorial design (2^3) was applied to systematically investigate the effects of three independent variables: PWLS content (1% and 5%), water-to-cement ratio (0.55 and 0.65), and curing period (7 and 28 days) [18]. The response variables measured were compressive strength (MPa), density (kg/m^3), and water absorption (%) [19]. A total of 16 experimental runs were conducted with three replicates for each run, resulting in 48 concrete cubes [20]. Design Expert software was used to perform ANOVA and numerical optimization [21]. This factorial design generated all possible combinations of factor levels and enabled the identification of both main effects and interaction effects on the measured responses [22].

3. Testing Procedures

3.1 Density

Density was measured before doing any destructive tests. This was to ensure that the concrete specimen is in a solid form. Each of the concrete cubes with the dimension size of 100 mm x 100 mm x 100 mm was measured using a Vernier caliper to calculate the volume, and the weight was measured using a calibrated electronic balance to obtain an accurate mass. Density results helped to assess the effect of PWLS on concrete weight and indicated whether the concrete becomes lighter with increasing PWLS content. Therefore, each of the concrete cubes was tested at curing ages of 7 and 28 days in order to determine changes in unit weight with age and PWLS replacement level. Density was calculated using the Equation 1 below:

$$\rho = \frac{M}{V} \tag{1}$$

3.2 Water Absorption

The purpose of the water absorption test was to evaluate the porosity and moisture uptake of concrete that contained PWLS. Each of the concrete cubes was oven-dried at a controlled temperature until a constant mass was reached and then immersed in the water tank for 24 hours. After the saturation, the concrete cube was removed, surface-dried, and weighed to obtain the saturated mass. This test provided insight into the influence of PWLS on concrete porosity and durability. Hence, it is conducted for 7 and 28 days to observe the property development over time. The saturated mass was recorded after surface-drying, and absorption was calculated using the Equation 2 below:

$$\text{Water absorption } \% = \frac{\text{Ms} - \text{Md}}{\text{Md}} \times 100 \tag{2}$$

3.3 Compressive Strength

The compressive strength test was the last step of mechanical and physical testing. This was because this test will destroy the specimen and make it hard to do other tests afterwards. To conduct this test, the concrete cube was removed from the curing tank, surface-dried, and placed centrally in a Compression Testing Machine (CTM). Then, the load was applied continuously at a controlled rate until the cube failed, and the maximum load was recorded. Moreover, the compressive strength test also determined the effect of the PWLS on the structural performance of concrete, and was conducted at 7 and 28 days to evaluate the strength development over a period of time. The maximum load was recorded, and strength was calculated using Equation 3 below:

$$\mathrm{f_c} = \frac{\mathrm{P}}{\mathrm{A}} \tag{3}$$

3.4 Data Analysis (ANOVA)

The experimental results obtained from the compressive strength test of concrete incorporating PWLS as a partial cement replacement were analyzed using statistical methods and the Design of Experiment (DOE) method. Thus, statistical analysis was performed using Analysis of Variance (ANOVA) at a 95% confidence level, where a p-value of less than 0.05 indicates a statistically significant difference using ANOVA for factorial design, while the adequacy of the developed model was assessed using the coefficient of determination R^2 and lack-of-fit tests [18].

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4. Results and Findings

4.1 X-Ray Fluorescence Data

Table 2 presents the chemical composition of PWLS that obtained from XRF analysis. The elemental analysis of the PWLS indicated that its composition was predominantly dominated by aluminum, iron, and silicon oxides, which together accounted for approximately 82.9% of the total mass percentage. The main oxides identified were Al_2O_3 (47.0%), Fe_2O_3 (24.4%), and SiO_2 (11.5%), with a smaller proportion of CaO (7.40%), and TiO_2 (2.48%). Minor constituents such as ZnO (0.799%), PbO (0.11%), and SO_3 (1.83%) were also detected, indicating the presence of residual contaminants from the PWLS processing

Table 2 *Chemical composition of PWLS*

Component	Formula	Mass (%)
Aluminum Oxide	Al_2O_3	47.0
Iron (III) Oxide	Fe_2O_3	24.4
Silicon Dioxide	SiO_2	11.5
Calcium Oxide	CaO	7.4
Titanium Dioxide	TiO_2	2.48
Sulfur Trioxide	SO_3	1.83
Zinc Oxide	ZnO	0.799
Lead (III) Oxide	PbO	0.111

4.2 Workability of Fresh Concrete

Table 3 presents the slump test results for all mix design including control sample. The slump test was conducted to evaluate the workability of fresh concrete that contains PWLS. A total of 17 mix designs, including a control sample (0% PWLS), were prepared in this study to investigate the effect of PWLS on fresh concrete properties.

Table 3 *Slump test result*

Mix Id	PWLS (%)	Water-to-cement Ratio (kg)	Slump Value (mm)
CM	0	0.57	30
M1	5	0.55	33
M2	5	0.65	54
M3	5	0.55	33
M4	1	0.55	30
M5	1	0.65	5
M6	5	0.55	33
M7	1	0.55	30
M8	1	0.65	51
M9	1	0.65	51
M10	1	0.65	51
M11	5	0.55	33
M12	5	0.65	54
M13	1	0.65	51
M14	5	0.65	54
M15	1	0.55	30
M16	5	0.55	33

The control mix exhibited a slump of 30 mm [23]. Mixes with higher water-to-cement ratios (0.65) showed improved slump values (51-54 mm) compared to those with lower ratios (0.55), which showed 30-33 mm [24]. The incorporation of PWLS influenced workability due to its fine particle size and high surface area, which increased water demand [17].

4.3 Analysis Using Design Expert

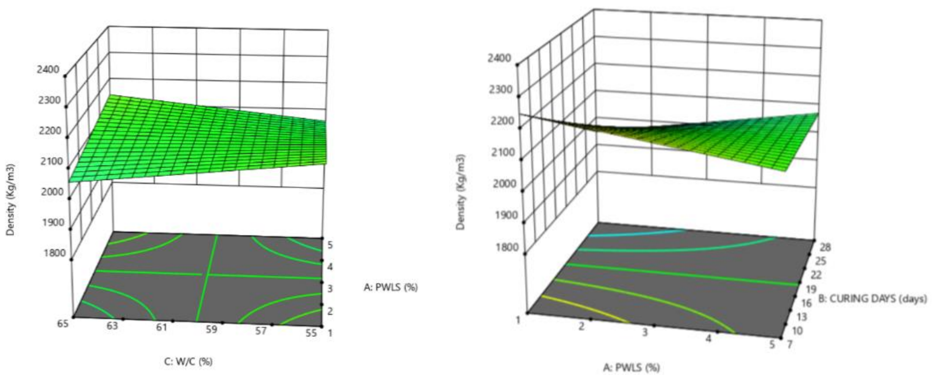
Table 4 summarizes the results for density, water absorption, and compressive strength for all mix designs.

Table 4 *Hardened concrete for all mix design*

Mix Id	PWLS (%)	Curing (days)	Water-to-cement Ratio (kg)	Density (kg/m^3)	Water Absorption (kg)	Compressive Strength (MPa)
M1	5	7	0.55	2040	2.07	5.30
M2	5	28	0.65	2100	2.19	8.80
M3	5	28	0.55	1970	2.16	31.30
M4	1	28	0.55	2000	2.27	23.80
M5	1	28	0.65	2030	2.13	8.80
M6	5	28	0.55	2060	2.12	9.00
M7	1	28	0.55	2030	2.10	29.50
M8	1	7	0.65	2220	2.25	27.40
M9	1	7	0.65	2230	2.23	31.40
M10	1	28	0.65	2020	2.17	9.80
M11	5	7	0.55	2230	2.26	9.80
M12	5	7	0.65	2310	2.33	37.90
M13	1	7	0.65	2320	2.33	37.30
M14	5	7	0.65	2150	2.22	10.40
M15	1	28	0.55	1890	2.27	26.20
M16	5	7	0.55	2020	2.10	10.20

4.3.1 Density Test

The density test results that obtained from all experimental runs were further analyzed using ANOVA in DE software to determine whether the chosen factors influence the density of the concrete sample. Factors that were used in this experiment were PWLS (A), curing duration (B), and water-to-cement ratio (C). ANOVA analysis was performed at 95% confidence level, where the P-value should be less than 0.05, which shows that the factors significantly affect the density response. the density model was statistically significant, where the F-value is 27.10, and the p-value is < 0.0001. As for the curing days, it exerted the strongest influence on density which F-value is 48.59, p-value is < 0.0001, proving that the longer the curing duration, the higher the density values. Furthermore, the interaction effects between factor A and factor B, which is the p-value of 0.0005, and between the factor A and factor C, which is the p-value is 0.0071, have been shown. These results prove that the influence of PWLS on density depends on both curing duration and water-to-cement ratio. The value for lack-of-fit was not significant, where the p-value is 0.1512, which confirms the adequacy of the developed model. Figures 1 present the 3D surface plot between PWLS content (A) and curing duration (B), and the 3D surface plot for the combined effect of PWLS content (A) and water-to-cement ratio (C) on density.



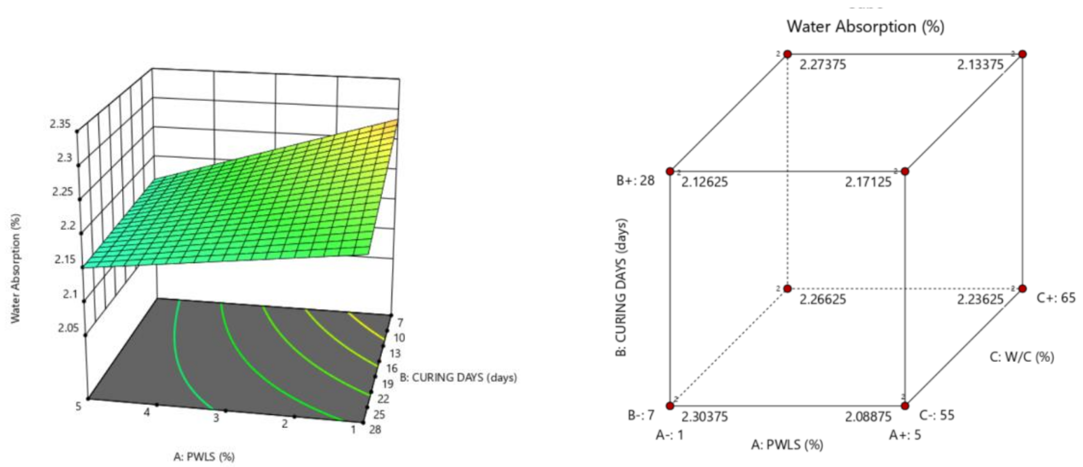
(a) Factor AC **(b) Factor AB**

Fig. 1 *(a) 3D surface plot for factor AC; (b) 3D surface plot for factor AB*

As shown in Figures 1 the density model for factor A and factor C on density with a constant curing duration of 17.5 days. The density values varied from approximately 2080 kg/m^3 to 2120 kg/m^3 across the design space. Hence, the values of the density occur where there is low PWLS content combined with low water-to-cement ratio and vice versa. On the other hand, the lower density values occurred when low PWLS levels were associated with a high water-to-cement ratio and vice versa. Therefore, from the contour plot, the curved contour lines indicate the presence of interaction between the PWLS and water-to-cement ratio, suggesting that the effect of one factor depends on the level of the other. However, for factor AB at a constant water-to-cement ratio of 0.60. The values for density were within the range of approximately 2000 kg/m^3 to 2200 kg/m^3. In terms of absolute density values, the highest density was observed at low PWLS content and shorter the curing durations, whereas the lower density values were obtained at the extended curing durations.

4.3.2 Water Absorption

The water absorption test is one of the important indicators of concrete durability, as it reflects the porosity and permeability of the concrete structure. A reduction in water absorption indicates better durability and reduced permeability of concrete, which enhances the resistance of concrete to its external environmental attacks (Guo et al., 2023). According to the water absorption results, the statistical test was significant, where the F-value is 15.07, and the p-value is 0.0002, which indicates that the selected factors significantly influence water absorption. PWLS content, curing duration, and water-to-cement ratio were identified as significant main factors. Furthermore, the three-factor interaction for factor ABC was highly significant where the F-value is 28.70 and the p-value is 0.0003. This shows that the influence of each factor depended on the simultaneous levels of the other factors. The lack-of-fit value was not significant, where the p-value is 0.0779, because it confirms that the developed model adequately represented the experimental data.



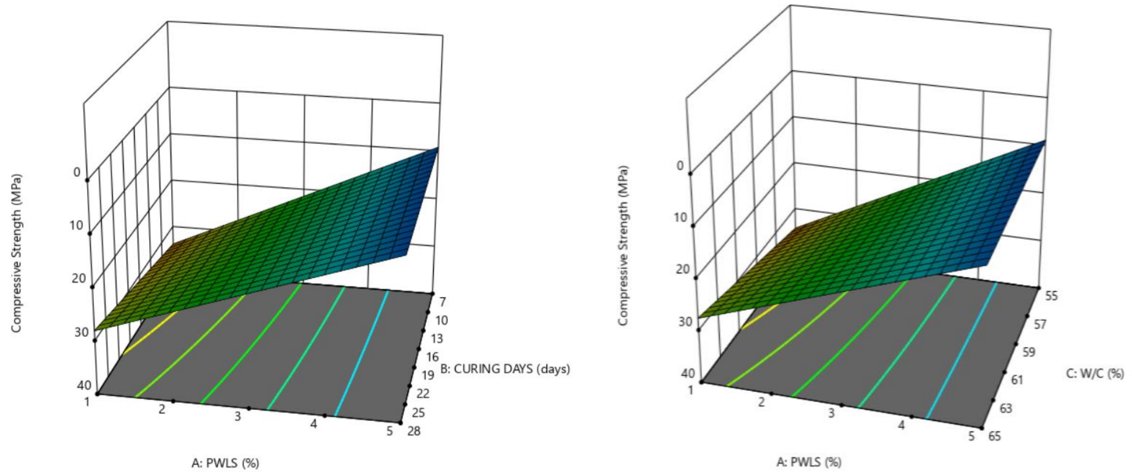
(a) Factor AB **(b) Factor ABC**

Fig. 2 *(a) 3D surface plot for factor AB; (b) 3D surface plot for factor ABC*

As shown in Figure 2, the water absorption for factor AB generally decreased as PWLS content increased from 1% to 5% and as the curing duration increased from 7 days to 28 days. The higher the water absorption value is, aproximately range from 2.26 % to 2.28 %. These values were observed at low PWLS contents, and the shorter the curing duration, where the lower the value is approximately in the range from 2.16 % to 2.18 % and occurred at the higher PWLS content and longer curing duration. As for factor ABC the results demonstrate a significant factor that increasing the PWLS content will generally reduce the water absorption. However, the results of this effect varied depending on curing duration and water-to-cement ratio. The minimum water absorption value is 2.09% occurred when the PWLS percentage was 5%, the curing duration was 7 days, and the water-to-cement ratio was 0.55 kg. It is evident from the analysis that water absorption depends on multiple interactions between the variables.

4.3.3 Compressive Strength

The influence of PWLS content and water-to-cement ratio on the compressive strength of concrete was analyzed in DE. The compressive strength results presented are the average values obtained from three specimens for each mix design. Based on the results obtained, the compressive strength is varied depending on the PWLS replacement levels and water-to-cement ratio. Generally, the mixes that contain lower PWLS content exhibited comparable or slightly higher compressive strength compared to the mixes with higher replacement levels [25]. Additionally, the mixes with the lower water-to-cement ratio showed higher compressive strength values due to reduced porosity and the improvement of concrete compactness. The results show that the factorial model for compressive strength was statistically significant, where the p-value is < 0.0001. These values indicate that the selected factors have significantly influenced the response. Thereby, among the main factors, factor A had the greatest effect on compressive strength because it had the highest F-value, which is 557.17 and p-value < 0.0001. In addition, factor B and factor C were also significant factors with the p-value of 0.0117 and 0.0089, respectively. Moreover, the significant interactions between AB, where the p-value is 0.0085, and AC, where the p-value is 0.0018, indicate that the effect of factor A on compressive strength varies depending on both factor A and C.



(a) AB **(b) AC**

Fig. 3 *(a) 3D surface plot for factor AB; (b) 3D surface plot for factor AC*

The PWLS content that showed in Figure 3 has the highest impact, followed by the water-to-cement ratio, and curing duration. The strength between the factor AB, are ranged from 5.3 MPa to 37.9 MPa. At the early curing duration 1 to 3 days, higher PWLS reduced the strength due to the delayed hydration, while the moderate PWS percentage 2% to 3% achieved higher strength after more than 5 days due to its pozzolanic activity. According to [25], a fewer hydration products such as C-S-H are formed, leading to lower strength development. Furthermore, the bonding performance between the cement and PWLS particles may be weaker compared to the conventional cementitious materials. The presence of the fine particles can affect the ITZ and lead to a less compact microstructure in certain mixtures, especially at higher replacement levels. However, lower water-to-cement ratio which is 55% facilitated better inclusion of PWLS, leading to the highest compressive strength 37.9 MPa for 1% to 2 % PWLS content with a water-to-cement ratio of 55% to 57%. These findings is align with the research on pretreated waste materials, where the optimal replacement levels improved the strength of the concrete over time because of the pozzolanic reaction and C-S-H formation [5], [26].

4.4 Numerical Optimization

Numerical optimization in DOE is a mathematical method that identifies the optimal combination of input factors to obtain the goal for the response. The software uses desirability functions in the range from 0 to 1 to determine how successfully the required goals can be reached for each variable target, such as maximizing compressive strength or minimizing cost. The process helps to locate those specific values of variables which lead to maximum desirability.

4.4.1 Criteria Setting

The numerical optimization criteria were established according to the objectives that needed to be achieved for each factor and response. As for the factors, PWLS (%), curing duration (days), and water-to-cement ratio (%) were all set to remain within their respective experimental ranges. However, for the response density (kg/m3), water absorption (%), and compressive strength were set to be maximized, while water absorption was set to be minimized. The details of the criteria setting are presented in Table 5, while the solutions are presented in Figure 4.

Table 5 *Criteria setting for numerical optimization*

Factors/Response	Goal	Lower value	Upper value
PWLS (%)	In range	1	5
Curing Duration (days)	In range	7	28
Water-to-cement ratio (%)	In range	55	65
Density (kg/m3)	Maximize	5.3	37.9
Water Absorption (%)	Minimize	1890	2320
Compressive Strength (MPa)	Maximize	2.07	2.33

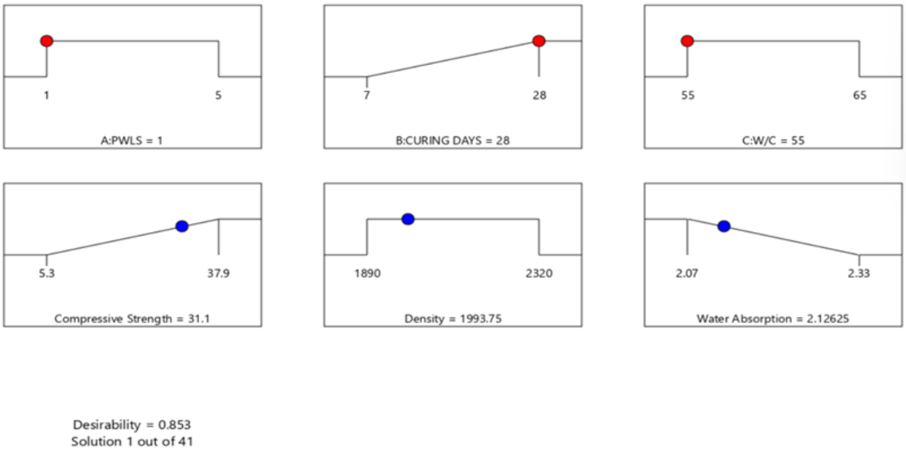


Fig. 4 *Solution for the criteria setting in design expert*

The optimal composition according to the numerical optimization was achieved with 1% PWLS, 28 days of curing duration, and 55% of water-to-cement ratio. The optimal composition showed that the predicted compressive strength would be 31.1 MPa, density 1993.75 kg/m^3, and water absorption was 2.126%. The overall desirability value was 0.853, indicating that the selected solution provided a good balance between high compressive strength, acceptable density, and low water absorption. Thus, the optimization plot also shows that the optimum solution occurred at the lowest PWLS content and lowest water-to-cement ratio, with maximum curing duration. These predicted results match with ANOVA analysis results, where the PWLS is strongly influenced by compressive strength, while the curing duration and water-to-cement ratio affect density and water absorption.

5. Discussion

The findings of this chapter collectively demonstrate that PWLS can be effectively utilized as a partial cement replacement in concrete at an optimal level of 1%, provided that appropriate curing (28 days) and water-to-cement ratio (55%) are maintained. Higher replacement levels (5%) consistently produced inferior mechanical performance across all tested conditions, with compressive strength reductions attributed to fewer hydration products, weaker interfacial transition zone bonding, and a less compact microstructure. Compared to the control sample (0% PWLS), the optimized 1% PWLS mixture demonstrates that modest cement replacement does not compromise concrete performance and may enhance durability through reduced water absorption. This study confirms that PWLS incorporation contributes to sustainable construction practices by reducing cement consumption, diverting waste from landfills, and promoting circular economy principles. However, the presence of sulphates and trace heavy metals in PWLS highlights the need for further investigation into long-term durability, leaching behaviour, and environmental implications prior to large-scale adoption in construction applications.

6. Conclusion

In conclusion, this study successfully demonstrated that PWLS can be used as a partial cement replacement in concrete at an optimum percentage level of 1%. Moreover, the XRF analysis has confirmed that the PWLS contains

82.9% of aluminum, iron, and silicon oxides, thereby making it suitable as a supplementary cementitious material. Among all factors that were tested, PWLS content had the greatest influence on compressive strength which the F-value is 557.17, and the p-value is < 0.0001, while the curing period influenced the density, where the F-value is 48.59, and p-value is < 0.0001. As for the numerical optimization, it showed that the ideal mix is 1% of PWLS, 28 days of curing, and 55% of water-to-cement ratio, which will produce predicted values of 31.1 MPa for compressive strength, 1993.75 kg/m^3 for density, and 2.126% water absorption with a desirability of 0.853. Overall, the replacing cement with 1% PWLS provides a balance between the mechanical performance and sustainable waste management, where it supports the circular economy principle in the construction industry.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Amira, Khairy;* ***data collection:*** *Batrisyia;* ***analysis and interpretation of results:*** *Batrisyia, Amira;* ***draft manuscript preparation:*** *Batrisyia, Amira, Farisha. All authors reviewed the results and approved the final version of the manuscript.*

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