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The Effect of Incorporating Polyvinyl Chloride Plastic Powder as Partial Cement Replacement on the Performance of Concrete

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Abstract - Plastic waste has given rise to numerous environmental issues due to its non-biodegradable nature. This research suggested the incorporation of polyvinyl chloride (PVC) plastic powder as partial cement replacement in concrete. The replacement levels of PVC waste powder (PWP) were 0%, 4%, 8%, 12%, and 16% by mass of cement. The concrete was cured for 7, 14 and 28 days before being subjected to mechanical strength tests (compressive and flexural strengths) and durability tests (porosity, water absorption tests). Results revealed that the workability of concrete with substitution of PWP as partial cement replacement increased in which replacing 16% of cement with PWP increased the workability by 56% as compared to the control specimen. The mechanical strength of concrete and durability decreased with the increase in PWP content. Nevertheless, up to 12% of PWP can be added into the concrete as the compressive strength was only 9% lower than the control specimen. All specimens achieved the required strength of 13.8 MPa to be classified as loadbearing concrete masonry units as specified in ASTM C90 – 14. Overall, only low quantities of PWP should be used to replace cement in concrete to maintain the quality of the concrete.

***Keywords*:** Polyvinyl Chloride (PVC) Power; Partial Cement Replacement; Mechanical Strength, Durability, Concrete Workability

1. Introduction

Environmental concerns involving plastic waste have become a rampant issue in Malaysia, which rank eighth among the world's top 10 nations with poorly handled plastic waste [1]. By 2018, annual unmanaged plastic waste generated in Malaysia was 0.94 million tons [2]. Meanwhile, the cement industry is facing a huge problem which is high carbon dioxide (CO_2) emissions from the production of cement [3]. CO_2 emission from the cement industry accounts for 5 – 7% of total worldwide CO_2 emission [4]. Despite this problem, the production of cement cannot be reduced due to the high consumption of cement by the construction industry. Cement is the major ingredient in concrete where the latter is the major and common building material applied extensively in the construction of buildings. Hence, finding an alternative material as the replacement of cement in the concrete manufacturing process may stop the increasing trend of the production of cement.

As a result, non-biodegradable plastic waste is a good choice to use as a replacement for cement. By recycling plastic waste as cement in concrete manufacturing, the environmental problem generated from plastic waste and the production of cement may be solved. Several research on incorporation of plastic waste products in concrete have been done in recent years. Most of the research investigated on employing plastic as a substitute for aggregates. Most authors concluded that the compressive strength of concrete gradually weakens with the increment in plastic weight percentage when the plastic waste is utilized as either coarse or fine aggregate replacement [5–7]. The hydrophobicity of plastic and its weak adhesion to cement paste limit the quantity of water necessary for cement hydration, are the causes for the reduction in compressive strength of concrete [5]. Islam et al. [6] further explained that, due to the plastic waste has no water absorption ability, the buildup of water in the transition zone increases the porosity and then, consequently, decreasing the compressive strength.

Nevertheless, insufficient literatures are available that discuss on the usage of plastic waste as powder to replace cement in concrete predominantly because of its non-cementitious nature that deteriorates the mechanical properties of concrete when mixed with cement paste [8]. Nevertheless, a few academies have conducted this study, with the majority showing that replacing cement with plastic powder has an adverse impact on the properties of concrete. Most research reported that substituting cement with plastic waste depletes the fresh and hardened properties of concrete. The poor adhesive strength between plastic particles and cement paste, the hydrophobic characteristic of plastic which restricts the movement of water and the absence of cementitious compound in plastic that should be responsible for the concrete strength development are all reasons for the unfavourable output obtained when cement is replaced by plastic waste [9–11].

In this study, PVC powder waste was used to as partial cement replacement in concrete. This is because PVC is one of the most popular thermoplastic polymers used with a global production of more than 61 million tons and a consumption capacity of 38.5 million tons [12]. However, unlike other plastics, recycling PVC is challenging because of its high chlorine content and various other additives that requires extensive dechlorination and dehydrocholorination treatments [13]. Hence, PVC is seldom recycled and is usually treated as a solid waste. To date, most studies focused on the utilization of PVC aggregate in concrete while there are only a few research done on utilizing PVC powder as partial cement replacement in concrete which was done by Gesoglu et al. [10], Manjunatha et al. [14], and Manjunatha et al. [15].

Two different conclusions were drawn from the authors. Manjunatha et al. [14] and Manjunatha et al. [15] claimed that the partially substituting cement with PVC powder by up to 15% can improve the strength of concrete. They attributed the positive result to the PVC powder's small particle size and specific gravity, which aided in voids packing and made concrete denser as compared to the control mix. Meanwhile, Gesoglu et al. [10] found that the strength of the concrete decreased with increasing PVC powder content because PVC inhibits the hydration of cement.

Hence, the objective of this study is to evaluate the properties of concrete incorporated with different concentrations of PVC powder as partial cement replacement. The performance of the concrete was evaluated using the workability, compressive strength, flexural strength, water absorption, porosity tests.

2. Materials and Methods

2.1. Materials

Ordinary Portland Cement (OPC) (MS EN 197-1:2014) was used in the production of concrete. Aggregates with sizes between 4.75 – 20 mm were utilized as coarse aggregates while river sand was used as fine aggregates.

In this study, polyvinyl chloride (PVC) powder was selected as a partial cement replacement. The PVC waste powder (PWP) was obtained from Shen Fei Enterprise, Ipoh, Perak, Malaysia. The produces recycled PVC raw materials by grinding PVC scraps into fine powder using a pulverize machine. The elemental composition of PWP is given in Table 1.

Table 1: Elemental composition of PWP.

Element	Composition	
	Weight (%)	**Atomic (%)**
Oxygen (O)	42.53	62.53
Chorine (Cl)	55.28	36.67
Copper (Cu)	1.35	0.50
Zinc (Zn)	0.83	0.30

2.2. Concrete Mix Design and Preparation

The mix proportion of concrete is shown in Table 2. The cement was partially replaced by 4%, 8%, 12%, and 16% of PWP in the concrete mix. The target grade of concrete produced in this experiment was M20 concrete. The water: cement: aggregate ratio was 1:1.5:3 and the water-cement ratio was 0.55.

During preparation, cement, PWP, and sand were thoroughly mixed thoroughly before adding in the coarse aggregates. Water was then added and the mixing process was continued. The concrete was cast into cubical, prismatic, and cylindrical molds. After 24 hours, the specimens were de-molded and cured underwater for 7, 14 and 28 days.

Table 2: Mix proportion of cubic concrete specimen (100 mm x 100 mm x 100 mm).

Sample	Materials (g)				
	PWP	Cement	Sand	Coarse aggregate	Water
CS	0	388	580	1163	213
PWP4	16	372	580	1163	213
PWP8	31	357	580	1163	213
PWP12	47	341	580	1163	213
PWP16	62	326	580	1163	213

CS: control specimen; PWP4: 4% substitution amount of PWP; PWP8: 8% substitution amount of PWP; PWP12**:** 12% substitution amount of PWP; PWP16:16% substitution amount of PWP.

2.3. Experimental Procedures
2.3.1 Slump Test
The fresh concrete mixtures were subjected to the slump test as according to BS EN 12350-2:2009 [16]. Fresh concrete mix was placed in a cone mold in three separate layers. Each layer was tamped 25 times. The mold was then lifted and the slump was measured based on the difference in height between the mold and the slumped concrete.

2.3.2 Mechanical Test
100 mm × 100 mm × 100 mm cubical concrete specimens were subjected to the compressive strength test in accordance with BS EN 12390-3:2009 [17] using a compressive testing machine. 40 mm x 40 mm x 160 mm prismatic concrete specimens were subjected to the flexural strength test in accordance with the BS EN 12390-5:2009 [18] using a material testing machine.

2.3.3 Porosity Test
The porosity test was carried out using the water displacement method. The cylindrical specimens (ø 45 mm × 40 mm) were first oven-dried to obtain their dry masses (W_{dry}). The specimens were then water-saturated through vacuum saturation and their water-saturated masses (W_{sat}) were measured. Lastly, the buoyant mass of the specimens (W_{buo}) was measured with a buoyant apparatus. The porosity of the specimens was calculated using Eq. (1).

$$Porosity = \frac{M_{sat} - M_{dry}}{M_{sat} - M_{buo}} \times 100\ \% \tag{1}$$

2.3.4 Water Adsorption Test
The water absorption test was conducted in accordance with BS1881-122:2011 [19] using 100 mm × 100 mm × 100 mm cubical concrete specimens. The percentage of water absorbed was calculated based on the mass difference before and after immersing the specimens in water for 30 mins.

2.3.5 Scanning Electron Microscopy (SEM)
Concrete specimens that were cured for 28 days were subjected for microanalysis using scanning electron microscopy (SEM).

3. Results and Discussion

3.1 Workability
According to Fig. 1, the workability of concrete did not change significantly when the percentage replacement of cement with PWP increased from 4% to 12%. The slump value of the control specimen, PWP4, PWP8, and PWP12, is 41 mm, 39 mm, 40 mm, and 43 mm, respectively. PWP4, PWP8 and PWP12 specimens obtained slump values nearly similar to the

control specimen (41 mm). The slump value difference between the PWP12 and control is <5%, indicating that replacing up to 12% of cement with PWP did not affect the workability of concrete.

In contrast, the PWP16 specimen showed a higher increase in workability as caused by the higher amount of free water in the mix. The replacement of hydrophilic cement by hydrophobic PWP in the concrete resulted in lesser water being absorbed by the cement particles, resulting in fresh concrete mix with higher fluidity and workability. The same phenomenon was noticed by Guendouz et al. [23] who used low-density polyethylene (LDPE) plastic powder to replace sand in concrete. The authors noted that this was due to the plastic has lower water absorbability compared to sand which resulting in more free water available in the mixture.

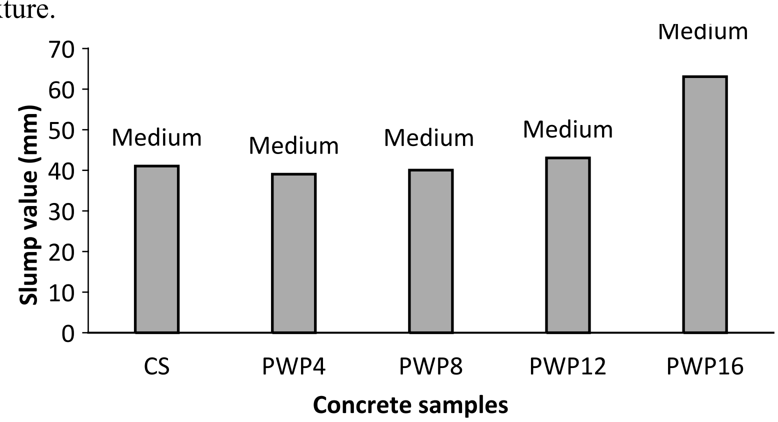

Fig. 1: Workability of fresh concrete specimens.

3.2 Compressive Strength

Fig. 2 illustrates the compressive strength of concrete at all replacement levels increased as the curing period increased. Despite PWP4 having lower cement content than the control specimen, the compressive strength of PWP4 specimen at 28 days (22.88 MPa) was similar to the control specimen (22.11 MPa). This could be associated to the PWP's filler effect. The added PWP acted as a filler to occupy the intergranular voids between cement particles and aggregate, therefore, enhancing the compactness of concrete [20]. The filler effect may compensate for the loss of cement during the hydration process in the PWP specimens.

However, further increasing the substitution level to 8% or above led to a decrease in compressive strength, accompanied by an increase in PWP. The PWP8, PWP12, and PWP16 specimens exhibited strength reductions of 8.5%, 9.0%, and 20.9%, respectively. This was due to the filler effect of PWP, which was insufficient to compensate for the negative impact of reduced cement content. As the PVC replacement level increased, there was a corresponding decline in the amount of cement available for hydration. This limitation restricted the hydration process between cement and water, thereby hindering the strength development of the concrete.

Furthermore, it was observed that some PVC powder floated on the surface of the concrete. Gesoglu et al. [10] justified that the specific gravity of PVC waste powder is vastly different to other concrete compositions. This weakens the interlocking between PVC particles and cement paste. Moreover, Manjunatha et al. [14] also reported that the incorporation of PWP in concrete may lead to the loss of cohesiveness between ingredient particles, lowering compressive strength. Another possible explanation for the drop in compressive strength caused by increasing the PVC ratio is the hydrophobic nature of PWP. Its hydrophobicity may limit the amount of water required from entering the concrete specimen's structure during the curing stage and obstructing hydration [21].

Nevertheless, the concrete specimens at 28 days, with all replacement levels except 16%, met the target strength of 20 MPa. The highest compressive strength was achieved by the PWP4 concrete, which measured 22.88 MPa. Furthermore, the strength reduction in the PWP8 and PWP12 concrete specimens was less than 10%. Based on the compressive strength test results, all the specimens achieved the required average strength of 13.8 MPa at all curing ages, qualifying them as load-bearing concrete masonry units as specified in ASTM C90-14 [22]. Given the significant strength reduction in PWP16 and its failure to meet the target strength of 20 MPa, the maximum allowable replacement percentage of PWP should be limited to 12% (PWP12). Among the tested levels, the optimum substitution ratio of PVC powder waste for partial cement replacement is 4% (PWP4).

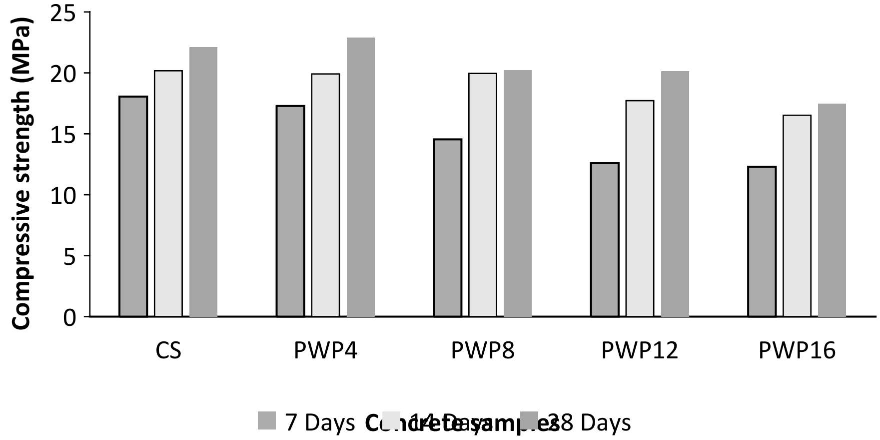

Fig. 2: Compressive strength of concrete samples after curing of 7 days, 14 days, and 28 days.

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3.3 Flexural Strength

Fig. 3 shows that the flexural strength of the concrete specimens with different replacement levels of PWP, which has a similar trendline to that of the compressive strength. PWP4 specimen attained a flexural strength (4.61 MPa) that was relatively similar to the control specimen (CS) (4.54 MPa).

Further increasing the replacement level to 8% and above resulted in a reduction in flexural strength. The PWP8, PWP12, and PWP16 specimens showed strength reductions of 19.3%, 24.3%, and 29.9%, respectively. The reduction in flexural strength for the PWP8 and PWP12 specimens was more pronounced compared to the decrease in compressive strength. The causes of the reduction in flexural strength are the same as those for the decrease in compressive strength, including the reduction in cement content, the hydrophobicity of PWP, and the lack of cohesiveness between cement particles, aggregates, and PWP, all of which disrupted the strength development of the concrete. Nevertheless, the results of the flexural strength tests were consistent with those of the compressive strength tests, both indicating that 4% was the optimal substitution level of PWP for partial cement replacement.

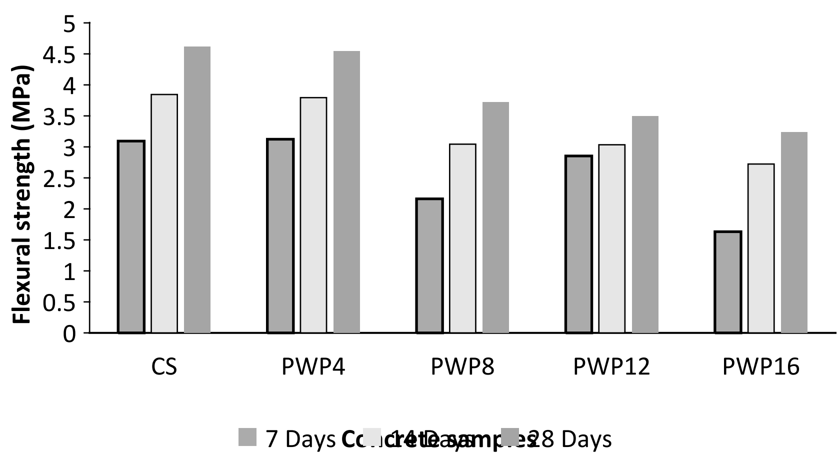


Fig. 3: Flexural strength of concrete samples after curing of 7 days, 14 days, and 28 days.

3.4 Porosity

Based on Fig. 4, the porosity of concrete appeared to increase with the amount of PWP at all curing ages. This is because the inclusion of PWP as a cement replacement leads to the formation of more pores or larger pore volumes in the concrete. The hydrophobic nature of plastic powder allows it to easily trap air during the mixing process, introducing air voids in the concrete [23]. PWP did not contribute to reducing the porosity of the concrete due to the lack of cementitious material, which is responsible for forming C-S-H gel and filling the pores.

Although the porosity increased with higher cement replacement levels of PWP, the porosity of the PWP4 concrete specimen was only slightly higher than that of the control specimen. The porosity of the control specimen after curing for 7, 14, and 28 days was 12.82%, 11.02%, and 10.39%, respectively. In comparison, the porosity of the PWP4 concrete specimen after curing for 7, 14, and 28 days was 13.12%, 11.39%, and 10.99%. The difference in porosity between the control specimen and PWP4 was less than 1%. Therefore, the optimal substitution level of PVC powder waste for partial cement replacement is 4%.

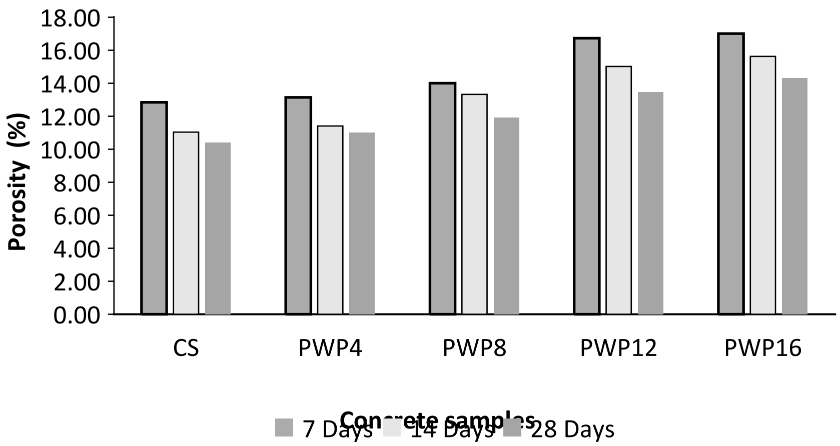


Fig. 4: Porosity of concrete samples after curing of 7 days, 14 days, and 28 days.

3.5 Water Absorption

Fig. 5 shows that the incorporation of PWP in concrete resulted in a higher water absorption rate at all curing ages. Water absorption is closely linked to the permeability of concrete, which, in turn, is related to its porosity. The hydrophobic nature of PWP, the absence of cementitious material, and the reduction in the amount of cement available for hydration, all affect the porosity of concrete, contributing to the increased water absorptivity of the specimens.

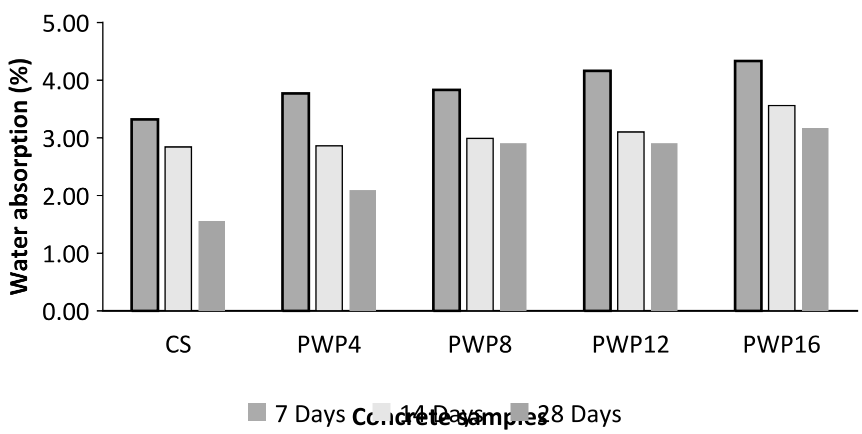


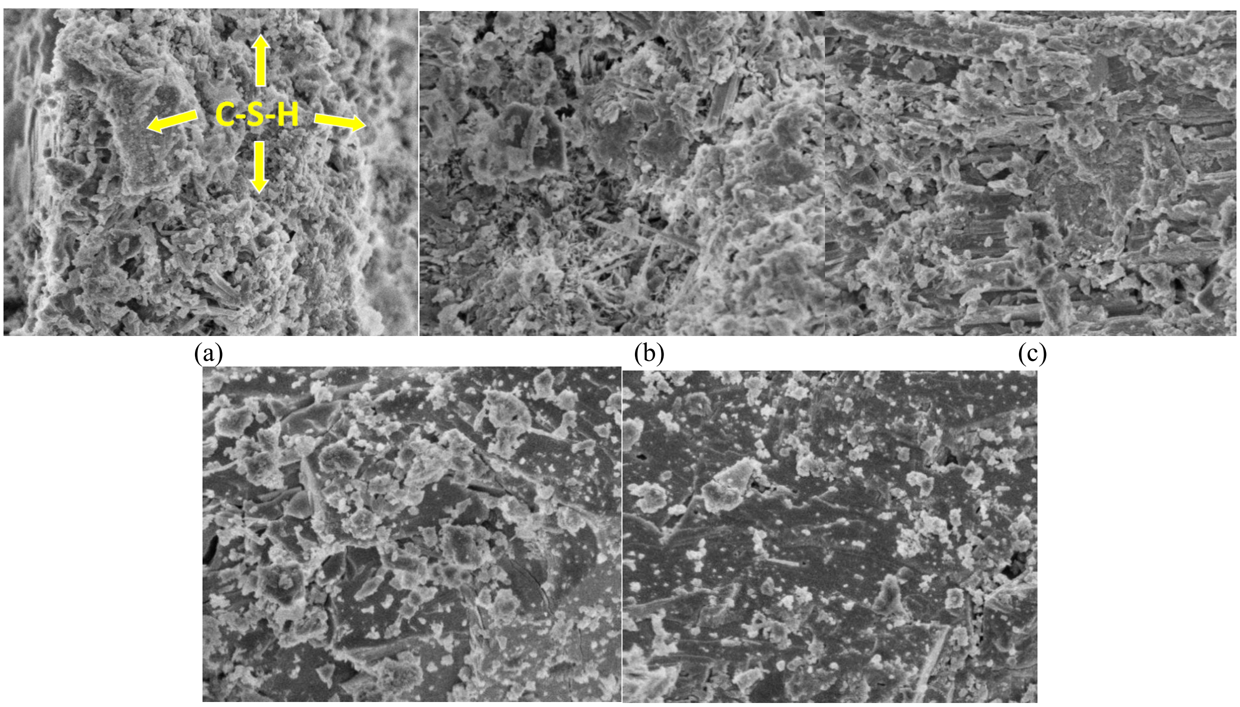
Fig. 5: Water absorption of concrete samples after curing of 7 days, 14 days, and 28 days

This finding aligns with the research by Geetha Devi et al. [9], who reported that the water absorption rate of concrete increased when more cement was replaced with PVC powder. The authors claimed that higher amount of PVC powder reduces the surface area available compared to Portland cement, leading to an increased absorption rate. Furthermore, PVC particles cause partial coverage of the aggregate surface, leaving void spaces.

3.6 Scanning Electron Microscopy (SEM)

The development and distribution of hydration products in the hydrated cement paste of the five different concrete mix proportions after a curing period of 28 days are shown in the figures below (Fig. 6a to Fig. 6e).

The SEM micrograph of CS (Fig. 6a) clearly displays the widespread formation of C-S-H gel in the hydrated cement paste, which is significant for higher strength development. Figures 6b to 6e show the SEM micrographs of the PWP4, PWP8, PWP12, and PWP16 concrete specimens. The distribution of C-S-H decreased as more cement was replaced by PWP. This reduction is due to the lack of chemical reaction between $Ca(OH)_2$ from the cement and PWP, which leads to a decrease in C-S-H formation. Consequently, the non-reactive PWP particles in the mix hinder the development of C-S-H, which subsequently affects the strength of the concrete. These SEM micrographs of all concrete specimens align with the results of the strength tests conducted in this study.



(a) (b) (c)
(d) (e)

Fig. 6: SEM micrograph at 10000 × magnification of (a) CS, (b) PWP4, (c) PWP8, (d) PWP12, and (e) PWP16.

4. Conclusion

The findings in this research can contribute to the development of green building materials. The following conclusions can be drawn based on the results of this study:

- The incorporation of PWP as partial cement replacement improved the workability of concrete mixtures by up to 56%.
- The incorporation of PWP weakens the strength of concrete, however, PWP may replace up to 12% of cement in concrete because it resulted in a small reduction in strength.

- The optimal substitution percentage of PWP for partial cement replacement is 4% since it resulted in a strength value that was nearly similar to the control specimen.
- The inclusion of PWP increased the porosity and water absorption of concrete, corresponding to lower durability of concrete.

Recently, companies from various sectors strive to emphasize on environmental, social & governance (ESG) goals. The construction industry can achieve ESG by selecting materials which are produced with minimal energy, such as waste materials. The results from this study may provide some insights in recycling PVC waste into concrete mixes. This preliminary research suggests that PVC powder can potentially be used as fillers in concrete when its replacement percentage is controlled within 12%. Further research can be done on more parameters and its influence on the long-term durability of concrete as plastic-based materials are prone to environmental degradation.

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