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UTILIZATION OF MODIFIED PLASTIC WASTE ON THE POROUS CONCRETE BLOCK CONTAINING FINE AGGREGATE

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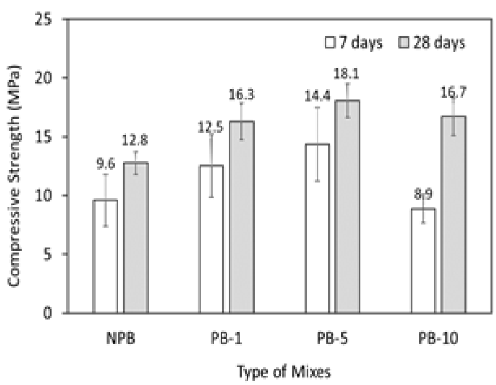
Graphical abstract



Abstract

Modification of plastic waste to be use as a replacement of coarse aggregate on the manufacturing of porous concrete block is presented in this paper. Different proportions of sand content were used with percentage of 1%, 5% and 10% by total weight of the sample to investigate its effects on the performance of porous concrete blocks based on some conducted tests i.e., compression and flexural load resistance, porosity, and infiltration rate tests. The results show that the porous concrete block with 5% of sand addition showed better strength properties compared to other mixtures. With 5% modified PET coarse aggregate, the compressive strength decreased for about 26%. Similar trends can be also observed when using PP and HDPE plastic aggregate. However, the inclusion of PET aggregate in porous concrete blocks with 5% of sand inclusion does not significantly show better strength indicating the weak bonding between plastic and cement mortar was performed in porous concrete block matrix as evident through the Scanning Electron Microscopy analysis. The formation of pores and higher permeability can be also expected after adding PET plastic waste as seen in porosity and infiltration rate results. Furthermore, the utilization of coarse aggregate made from plastic waste in porous concrete blocks containing fine aggregate is a potential solution on plastic waste management for permeable pavement including foot traffic and light load application.

Keywords: Plastic aggregate; porous concrete blocks; fine aggregate; pavement; permeability

1.0 INTRODUCTION

The urban environment settings in this digital era have been an issue, particularly in developing countries due to the increase in population and activities. Besides the social problems, housing, employment, pollution, welfare and security issues [1], one of the important issues is how to establish the infrastructure that supports the emergency management plans for natural disasters.

Nowadays, porous concrete as a pavement material has been claimed as one of the most promising sustainable materials that leads to the improvement of water storm management especially to the area that has the risk of flood disasters. Porous pavement material is able to catch up to 45% of water making it suitable for waterlogged areas, parking area and pedestrian path in gardens.

From its definition, porous concrete that is also known as previous concrete is concrete with high permeability which is formed by the interconnected pores (range of 0.08 – 0.32 in or 2-8 mm) and void content ranges from 11 – 35% [2], [3]. Another advantages that can be found in porous concrete are noise absorption where can significantly reduce the generation of noise from tire-pavement by 4 to 8 db [4], lower the thermal conductivity as the porosity increase [5] and high slip resistance that indicated by additional contact pressure and less potential of ponding water and surface freezing that indicated the beneficial surface condition for both hot and winter seasons, as studied by [6].

As the environmental concerns raised recently, especially on the plastic waste management, scholars and researchers have addressed comprehensive research on the potential modification of plastic waste to become construction material to support the sustainability sector with manifold environmental advantages.

Plastics are generally used in human daily life as for packaging, containers, protective apparels (e.g., helmets, airbags) or for medical purposes (e.g., blood bags, tubing) and many fields related to industrial applications [7]. Type of plastics including Polyethylene Terephthalate (PET), Polyvinyl Chloride (PVC), Polypropylene (PP), Polystyrene (PS) are the most recycled plastics while other types are also available for common use. Each type of plastic has their own properties based on the chemical bonding and polymeric composition during manufacture that affects its characteristics.

In the construction sector, the options for plastic waste disposal have been utilized as a substitute or replace material in a concrete mixture.

Kore (2018) [8] reviewed some various studies on the feasibility of utilizing plastic waste in concrete mixes and concluded that the inclusion of plastic waste maintained the concrete properties and improved the workability of mixtures. This review also obtained satisfactory results on concrete properties when the plastic waste replaced the sand content at a percentage of replacement was 10%. The effect of using PET plastic waste as a sand replacement was then investigated more by Almeshal *et al*., 2020 [9]. This study found that replacing sand with PET aggregate with a percentage of 10%, 20%, and 30% lower the compression load resistance from 1.2% to 31%. The percentage of strength loss increased as the percentage of plastic aggregate was increased. This study concluded the potential use of PET plastic aggregate in concrete that can be applied as medians in highway, pavement, and any structural application where high resistance on compression is not expected. On the other hand, it can be an ideal solution to maximize the influence of pervious concrete in controlling storm water and re-charging the ground water. However, extensive research should be explored more for better physical and mechanical properties of pervious concrete with plastic aggregate inclusion as pavement structure element.

Considering the method of plastic waste production, some studies investigated the effect of the treatment process before using the plastic waste into concrete mixtures. The treatment of plastic waste is suggested to modify the characteristic of plastic aggregate that resulted in increasing the bond strength with cement paste. Treated plastic aggregate typed PET before using as an aggregate replacement in concrete have been studied by Lee *et al*., (2019) [10]. This study found the improvement of strength properties due to the enhancement of bond strength under chemical treatment of plastic waste. The use of $Ca(ClO)_2$ performed better results compared to H_2 and H_2O_2. The elemental analysis showed the lowest Ca/Si ratio formed in concrete with PET aggregate treated with $Ca(ClO)_2$ that can be the reason for strength improvement. However, it was obtained that there was no effect found on the density of concrete after the chemical treatment. El-Nadoury (2022) [11] also studied the use of treated PET plastic waste by using 5% polystyrene and 5% PKHH-phenoxy resin to increase the coarseness of the plastic aggregate as a sand replacement. Based on the results, this study confirmed the bond strength and mechanical properties improvement when the plastic aggregate was treated. In this experiment, replacing 20 % of sand with treated PET plastic waste in a concrete mixture exhibited 32 MPa of compressive strength making it possible to be used for structural application. From the treatment process of plastic waste particles, it can be discovered that the surface texture, size, and shape are important factors to have an impact upon concrete performance as also found by Mohammed *et al*., (2020) [12]. The author also discussed the possibility of using method of microwave curing to improve the bond capacity when including plastic waste into concrete mixtures.

Within most literature studies conducted on the area of artificial plastic aggregate production as an additive material in concrete, using strip cut particles form have been researched more than the melted particles [13-15]. This can be because of its production costs and its amalgamation tendency that can be performed during the melting process. On the other hand, PET-typed has been the most frequently studied but lacks research works found in developing countries (Mercante, 2018) [16]. Most of the studies on plastic waste use also based on the authors best knowledge were concentrated for concrete application including for paving block production [17], [18], [19] where the usage of modified plastic waste type PET as an aggregate to partially replace the natural coarse aggregate in porous concrete block is still at early stage of development particularly when fine aggregate content is involved in the mixture. The addition of sand is expected to improve the strength properties of pervious concrete block with plastic waste aggregate since sand leads to thicker the coverage of the cement paste and contributes the improvement of raveling, skid resistance and flexural strength [20]. Therefore, the study objectives are to investigate the influences of modified PET plastic waste as a natural coarse aggregate replacement based on compression and flexural load resistance, porosity, and infiltration rate of porous concrete block containing fine aggregate. The use of PET plastic aggregate was performed on porous concrete blocks containing 5% sand addition whereas based on the compressive strength test conducted in this research, 5% of sand addition exhibited highest compressive strength compared to 0%, 1% and 10% sand addition. This study also observed the influence of using other types of plastic waste such as PP and HDPE but focusing only for compressive strength tests. The research findings are expected would be beneficial in sharpen the ideas on the potential application of plastic waste aggregate as a natural coarse aggregate replacement in porous concrete block containing certain percentage of fine aggregate that can be proposed to put in practical use as an ideal solution to control stormwater, recharging of groundwater while keeping the sustainability and supporting environmental aspects [21].

2.0 METHODOLOGY

Portland Cement Composite (PCC), coarse aggregate with size of 5-10mm, and local sand as a fine aggregate were used as main materials. Plastic waste type PET (Polyethylene Terephthalate), which is normally used for bottled drinking water was sorted out and collected from the Sumompo Landfill site in Manado City. The sorting process is shown in Figure 1. Figure 2 presents the process of melting the plastic waste (1a) and manual crushing of the plastic aggregate (1b). The appearance of the modified plastic aggregate after crushing can be seen in Figure 3.

Figure 1 Sorting out PET plastic waste in the landfill site

In order to form the coarse aggregate from PET plastic material, the plastic was cut into pieces manually and heated under temperature of 150-180^0 C until it melted. In this case, the temperature is the main factor that will significantly affect the density of the plastic aggregate. When the temperature reaches more than 180^{0}C, the high brittleness of plastic can be expected. After the melting process, the hardened plastic was modified to become plastic aggregate by crushing it manually into a size of 5-10mm which is same as the size of natural coarse aggregate. The similar procedure was used when using other plastic types i.e., PP and HDPE for compression test.

a b

Figure 2 Manufacturing process of plastic aggregate including melting (a) and crushing (b)

Figure 3 Modified PET plastic aggregate

The experimental method was performed in two stages. In the first stage, the investigation was focused on the effect of different percentages of fine aggregate added into the mixture of porous concrete blocks according to the compression load resistance results at the 7th and 28th day. The variation used was 1% (PB-1), 5% (PB-5) and 10% (PB-10) by weight of the volume and the control mixture (NPB) without sand inclusion. In this phase, the compressive strength with different types of plastic aggregate i.e., PET, PP and HDPE (PB-5-PET/PP/HDPE) was also evaluated as a coarse aggregate replacement of in mixture with 5% of sand addition. In this stage, the porous concrete block mixture containing 5% fine aggregate was selected as it reached the highest compressive strength compared to the other mixtures (PB-1 and PB-10). The resistance on compression load was conducted based on ASTM C936 "Standard specification for solid concrete interlocking paving units" [22].

The second phase involves flexural strength test, porosity and infiltration rate tests conducted on porous concrete block mixture containing 1%, 5%, and 10% of sand addition, and mixture with 5% replacement of sand combined with 5% of PET plastic waste by wt. of coarse aggregate. Only PET plastic aggregate was continuously used in this stage due to its availability. In the second phase, the investigation was conducted on the 28th day only. The mixture proportions can be seen in Table 1. In this mixture water to cement ratio of 0.3 was used with addition of 0.5% superplasticizer by wt. of cement to control the consistency of the mixture. The tests conducted was followed some standards i.e., ASTM C78/C78M-22 "Standard test method for flexural strength of concrete (using simple beam with third-point loading)" [23], Japan Concrete Institute for porosity test [24], and ASTM C1701/C1701M-17a "Standard test method for infiltration rate of in place pervious concrete" [25].

The porous concrete specimens were prepared using paving block formwork with size of 210mm x 110mm x 80mm cast at one of paving block industries available in Manado City, North Sulawesi Province, Indonesia. Figure 4 shows the manufacturing process when the plastic waste was added into the mixture (4a) and the porous concrete block after casting (4b) while Figure 5 shows the conducted tests including compressive strength (5a) and infiltration rate (5b) tests.

Table 1 Porous concrete mixture (%)

Mix	Cement	CA	FA	PA
NPB	100	30	-	-
PB-1	100	30	1	-
PB-5	100	30	5	-
PB-10	100	30	10	-
PB-5*	100	25	5	5

Notes: CA=Coarse Aggregate; FA=Fine Aggregate; PA=Plastic Aggregate; PB-5*=Porous block containing 5% FA+5% PET/PP/HDPE

a b

Figure 4 (a) Combining PET aggregate into porous concrete block mixtures and (b) Porous concrete block after casting

a b

Figure 5 (a) Compressive strength and (b) Infiltration rate test set-up

3.0 RESULTS AND DISCUSSION

A. Compression load resistance of porous concrete block with different percentage of fine aggregate

Figure 6 illustrates the effect of adding sand in the porous concrete block mixture. It is clearly seen the improvement of strength when adding sand where PB-5 exhibited the highest compressive strength when compared to normal porous block samples and the other mixtures containing 1% and 10% of sand.

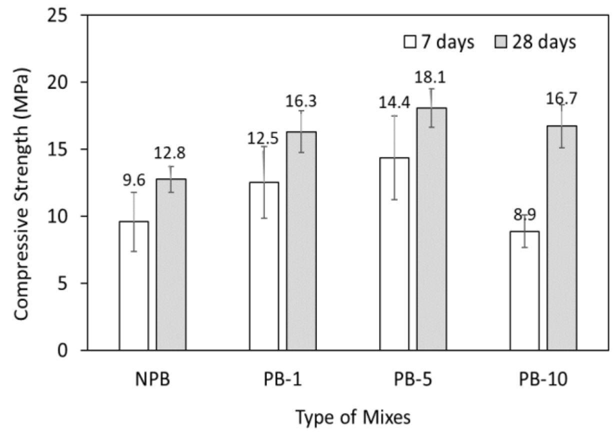


Figure 6 Compressive strength of porous concrete block with different sand content

This figure indicates that the mixture proportions containing up to 10% of sand by volume should be well proportioned to achieve the desired strength and acceptable density and permeability. In this case, increasing the sand content into the mixture, increasing the surface area makes the low water to cement ratio of 0.3 does not sufficiently complete the paste thickness surrounding coarse aggregate that can result in an inadequate bond strength. Based on this study, the presence of sand at the percentage of 1% and 5% provides denser pore block structure and sufficiently improves the compressive strength when compared to the normal porous concrete block. The addition of 1% and 5% of sand was observed to improve the compressive strength of normal porous blocks from 23-33% and 21-29%, at 7 and 28 days, respectively. In the review study conducted by [26], the authors also concluded the improvement of strength and durability properties due to the addition of fine aggregate that can be due to the enhancement of interfacial bond as also reported by [27] with percentage of fine aggregate addition can be ranged from 5 to 15% to satisfy the application as a sub-base in a rigid pavement. In this experiment, the porous concrete mixture with 5% of sand was then selected for further investigation on the effect of replacing coarse aggregate with different type of plastic waste aggregate as discussed in the next section.

B. Compression load resistance of porous concrete block containing 5% fine aggregate and 5% different type of plastic aggregate

Figure 7 illustrates the compressive load resistance results of porous concrete blocks containing different types of plastic aggregate i.e., PET, PP and HDPE. In this part, 5% of plastic waste aggregate was used to replace coarse aggregate in porous concrete block mixtures containing 5% of sand. From the figures, the phenomenon of low compressive strength when including the plastic coarse aggregate in all mixtures can be reported. Although there is no significant different of the compressive strength results at all days among the mixtures containing plastic aggregate, it can be clearly observed that plastic waste aggregate tends to reduce the compressive strength (23% lower than sample without plastic aggregate) of the porous concrete blocks due to its hydrophobic nature that lower the adhesive between plastic waste and cement paste [15]. A small comparable result can be observed between plastic aggregate type PET and HDPE that exhibits a little bit higher compressive strength than the mixture with PP plastic aggregate. This trend can be due to the higher impact strength and resistance on tension than PP. Abu-Saleem *et al*. (2021) [28] also reported the characteristics of PET plastic waste when compared with HDPE and PP materials. They invented that the addition of PET at the percentage of 10% and 20% replacement of coarse aggregate improved the compressive load resistance of concrete compared to mixture with HDPE and PP inclusions at the same percentage. This study also mentioned about the higher resistance to abrasion for samples containing PET waste and claimed the existence of exfoliators and scratches on the plastic surface through the SEM analysis indicating the improvement of bond with cement paste. When used as a fine aggregate replacement, PET in concrete is recommended to be less than 15% [29]. Furthermore, it can be concluded that the morphology and surface texture of different types of plastic waste aggregate are responsible for the properties of porous concrete blocks. Additionally, although the loss of strength can be expected due to the addition of plastic waste, it is still possible to be limited by adjusting the mix design and plastic treatment based on the characteristics of each different type of plastic. For a conventional concrete, the use of plastic aggregate should be less than 25% when replacing natural aggregate to achieve the desirable requirement of structural concrete for pavement applications. The use of cementitious materials such as GGBFS [30], FA [31], metakaolin [32], and silica fume [33], also reduction of the size of nature coarse aggregate can be an alternative solution in enhancing the mechanical properties of pervious concrete that can be expected also when including plastic waste aggregate [34].

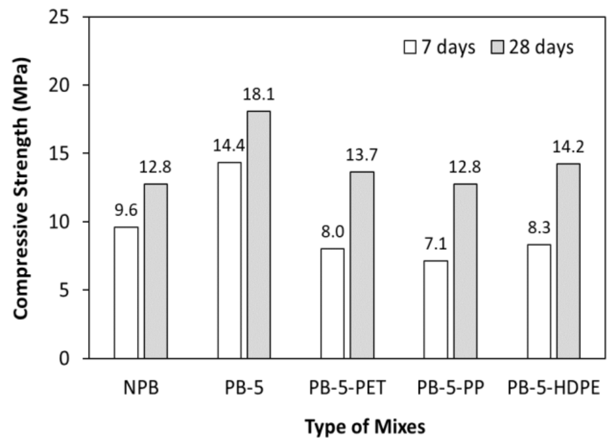


Figure 7 Compressive strength of porous concrete block with 5% of different type of plastic as coarse aggregate replacement

C. Flexural load resistance of porous concrete block with fine aggregate and 5%PET

Figure 8 shows the flexural strength values of different type of mixtures containing different percentages of sand addition compared to normal and 5% PET aggregate with 5% of sand addition mixtures.

Based on the figure, the addition of sand in a porous concrete block mixture enhances the flexural strength at the 28th day. When 5% PET coarse aggregate was used, the strength was slightly decreased from 4.73 MPa to 4.33 MPa indicating that there is no significant effect found in porous block mixture when replacing coarse aggregate with 5% PET aggregate. However, the ductility improvement can be expected when using PET aggregate in porous concrete blocks because of more flexible properties of plastic aggregate as discussed by Abukhetalla, 2021 [35]. In this study, the mechanism observed for drop strengths induced by the plastic waste inclusion can be due to reduction in adhesive performance between the surface of plastic and the cement hydration products, larger pore structure due to the plastic addition and the hydrophobic nature of plastic that restricts the water movement to enter the concrete structure during the period of curing. A study from [29] observed the possibility of accumulating many PET particles in one area that produced weak zones where the failure points begin.

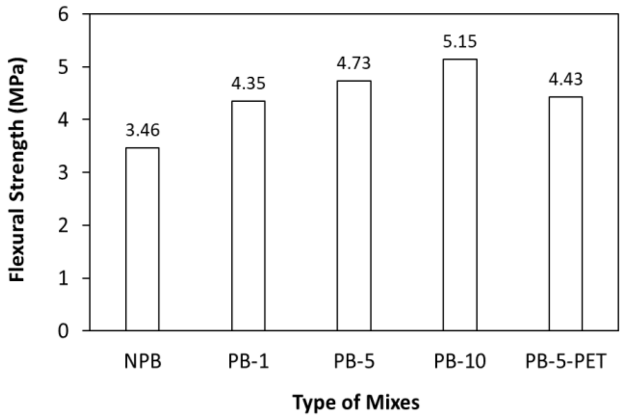


Figure 8 Flexural strength of porous concrete block with different type of mixtures

D. Porosity of porous concrete block with fine aggregate and 5% PET

Porosity values represent the pores volume induced by the inclusion of PET aggregate in porous concrete block mixtures. The porosity can be a parameter that should be considered in creating sufficient pores to permits stormwater to drain through the porous concrete block [36]. In this experiment, the porosity was calculated based on the formula below:

$$A_t\ (\%) = 1 - \frac{(W_2 - W_1)/\rho_W}{V_1}\ x\ 100 \qquad (1)$$

Where: V_1=volume of specimen; W_1=mass of sample in water after water curing; W_2=mass of sample after 24 hour left at room temperature

As seen in Figure 9, the total porosity (At) of porous concrete block with 10% of sand addition obtained the lowest percentage of voids compared to other mixtures. It is noticed that the inclusion of sand reduced the porosity significantly as the sand content increased. Moreover, when 5% of PET aggregate was added, the higher ratio of voids was performed but does not show significant difference when compared to normal porous block. However, more voids could be the reasons for strength reduction after inclusion of plastic waste aggregate in porous concrete blocks.

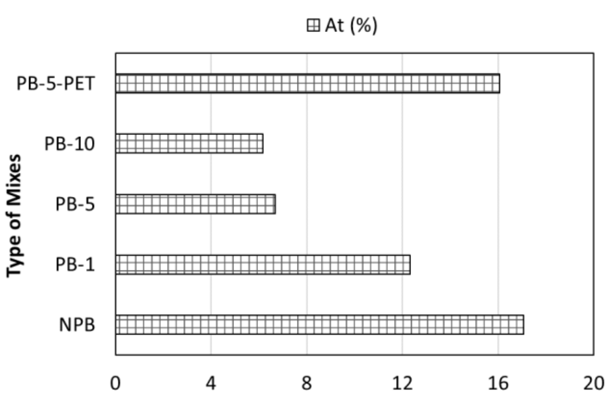


Figure 9 Porosity of porous concrete block with different type of mixtures

E. Infiltration rate of porous concrete block with fine aggregate and 5% PET

In this test, the total water of around 1 liter (M) was poured into the ring with diameter of 8cm (D) and the elapsed time started from the water connected to the surface and disappeared from the surface of the porous concrete block sample (t). The infiltration rate was then calculated based on the formula in Eq. (2) where K=4 583 666 000 in SI units.

$$I = \frac{K\,M}{(D^2\,t)} \qquad (2)$$

The infiltration rate results of porous concrete blocks can be seen in Table 2.

Table 2 Infiltration rate of different type of mixtures

Type of Mixes	Infiltration Rate (mm/sec)	Average (mm/sec)
NPB	11.05	10.50
	9.95	
PB-1	6.22	6.42
	6.63	
PB-5	5.43	5.64
	5.85	
PB-10	3.98	4.12
	4.26	
PB-5-PET	5.53	5.87
	6.22	

It can be clearly observed that the addition of sand in the mixture resulted in the reduction of the permeability of the porous concrete block represented by the lower infiltration rate performed by PB-1, PB-5, and PB-10 when compared to normal porous concrete block (NPB). When the mixture containing 5% of sand content is mixed with 5% PET coarse aggregate, there is an insignificant difference in infiltration rate of PB-5 and PB-5-PET. In this case, the plastic aggregate modifies the pore structure and increases the percentage of voids that effectively accelerates the water flow passed through the samples. This can be due to the flat and regular surface of plastic waste aggregate that effects the increase of infiltration rate in concrete mixture as also observed by a study in reference [37].

F. Scanning Electron Microscopy of porous concrete block containing plastic aggregate

The surface morphology of modified PET aggregate and the bonding performance with cement paste (ITZ zone) can be seen in SEM images as shown in Figure 10 below.

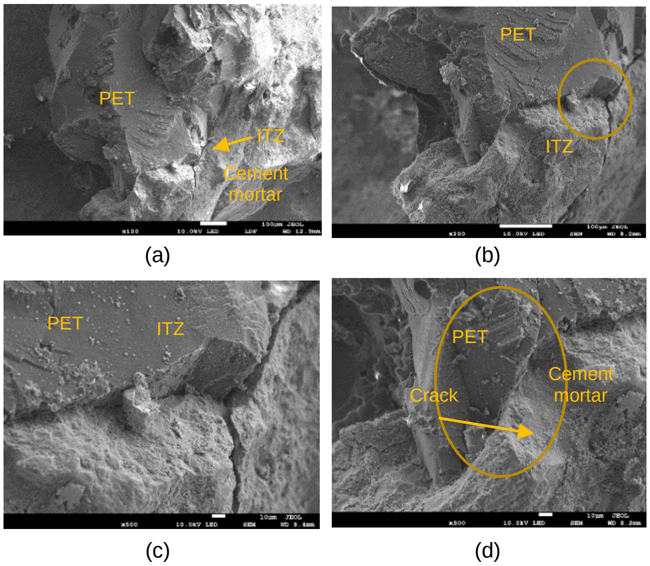


Figure 10 SEM images of plastic waste bonding in cement mortar matrix

The interfacial transition zone (ITZ) that is known as the weakest link that affects the overall properties of porous concrete block was examined through this microstructure analysis. Based on the analysis, the weaker link between PET and cement mortar can be observed that is visible in the formation of gaps (see Figure 10a, 10b, and 10c). Figure 10d shows some crack lines appearing in cement mortar while there are no crack lines appearing on the surface of plastic aggregate. This is an indication that at one point of view, the plastic aggregate has a higher hardness compared to cement mortar that may influence the strength properties of porous concrete block when sufficiently proportioned. Mixing process is also important to make sure that the plastic waste aggregate is uniformly distributed in the mixture. A poor bonding between plastic aggregate and cement paste is also reported in a study conducted by [38]. Inadequate connection formed due to plastic aggregate addition can be due to the excessive water in the mixture that resulted in developing a film around the aggregates thus poor interaction in the ITZ area can be expected.

4.0 CONCLUSION

The inclusion of fine aggregate with a percentage of 1-5% by total weight of materials improves the strength properties of normal porous concrete blocks. However, when the replacement content was increased to 10%, the reduction of compressive strength can be expected with a slight increase in flexural strength. Mixtures should be properly designed since the aggregate volume, water to cement ratio and the aggregate sizes affect the binder characteristics that are associated with the strength performance of porous concrete blocks. When considering the different types of plastic waste, the porous concrete block containing plastic aggregate type PET and HDPE plastic waste reach higher compressive strength than mixture with PP type aggregate. Nevertheless, lack of bonding can be expected when using the plastic aggregate as a coarse aggregate replacement. Therefore, the improvement of surface texture should be considered especially when the level of percentage is more than 5%. In this case, chemical treatment can be considered for future research. To investigate more the bonding properties, extended tests on tensile and flexural strength including the bonding test are recommended. Based on the experimental results, the strength performance and pores of pervious concrete block containing fine aggregate and plastic waste aggregate are mainly influenced by the aggregate size and shape, gradations of all aggregates involved in the mixture, binder characteristics including aggregate volume and cement content, type of plastic waste, and manufacturing method. The utilization of modified PET aggregate as construction material in porous concrete blocks is suitable for foot traffic and light load application. However, standard for manufacturing processes including the guidelines on the selection and preparation of plastic waste aggregate is essentially needed for immediate application.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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