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The Effects of Domestic Plastic Waste on Concrete Properties: Sustainable Replacement of Aggregates

Siti Hamizah Ahmad[1], Noor Dina Md Amin[1]*, Noorwirdawati Ali[1]

[1] *Faculty of Civil Engineering and Built Environment*
Universiti Tun Hussein Onn Malaysia, Batu Pahat, 86400, MALAYSIA

*Corresponding Author: dina@uthm.edu.my
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Abstract

Malaysia is the largest contributor to plastic waste disposal in Southeast Asia. It is due to the fact that, with the existing way of life, users choose to use plastic in their daily lives without knowing the impact of its use. Plastic is a material that does not easily break down and dissolve naturally. It requires a long period of time to break down and decompose. So, the concept of recycling is one way to save nature and this concept can also be practiced in the construction sector such as construction materials. Therefore, this study identifies the appropriate ratio of cement, water, plastic replacement, and aggregate in the concrete. In addition, this study determines the effect of domestic replacement of waste plastic on concrete properties. The third objective is to compare the concretes with admixtures without plastic with admixtures with plastic replacement along with fine aggregate and coarse aggregate. This study focuses on the use of polyethylene terephthalate (PET) plastic with 10% and 20% replacement levels in both fine aggregate and coarse aggregate. The appropriate ratio for the concrete aggregate is identified by using the DoE (Department of Environment) method. Several tests were conducted to test the workability of the concrete, namely slump test, density for hardened concrete, water absorption and compressive strength. Based on the results obtained, the density of coarse aggregate plastic concretes (DP10C, DP20C) is higher than that of fine aggregate plastic concretes (DP10F, DP20F). Meanwhile, the water absorption rate for coarse aggregate plastic concretes (DP10C) is lower than fine aggregate (DP10F) for both 7 days and 28 days curing. As for compressive strength test, the replacement of concrete with coarse aggregate (DP20C) is higher than fine aggregate (DP20F). The replacement for fine aggregate has a limit up to 10%, if exceeding that percentage, the strength of concrete will decrease drastically. In conclusion, the replacement of plastic in concrete has a good effect on the environment and the concept of sustainable concrete is achieved.

1. Introduction

In Southeast Asia, Malaysia is the country that contributes the most to the disposal of plastic waste (Asrol, 2022; United Nations Member, 2021). This is because, given the current way of life, people prefer to use plastic without considering the consequences involved with doing so. Plastic is a material that dissolves naturally but does not break down quickly. It takes a while to decompose and breakdown. However, there are several methods to dispose of the plastic waste. Among them are landfills, incineration, biodegradable plastic, and also

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recycling plastic (WB Waste, 2019). Each of these methods has its own weaknesses. For landfills, it takes a lot of areas for the plastic to be disposed of (Vivek et al., 2023)and the light plastic is easily washed into the sea or in other areas and makes the area unmanageable. Incineration methods have already shown their obvious effects on nature, namely the depletion of the ozone layer. Meanwhile, biodegradable plastic consumes relatively high production costs compared to normal plastic. Therefore, the concept of 3R, reduce, reuse, recycle, encourages users to recycle plastic.

The concept of recycling is also practiced in the construction sector by using it in building materials such as concrete. The combination of concrete and plastic produces a sustainable building material product. For some past studies call this concrete mixture green concrete because of the replacement of natural materials with plastic (Ahdal et al. 2022) and this concrete mixture can reduce the negative impact on nature. This study uses plastic as a partial substitute for sand and aggregate. This is because aggregate and sand are natural materials that are taken from open spaces called quarries. This activity clearly damages the natural environment and the way this resource is taken adds more pollution to nature as the eruption that is done will produce dust flying in the air and then air pollution occurs. Because of that, this study tries to reduce the existing environmental pollution. This mixture of plastic with cement and water were tested for its strength and the advantages of its use was studied so that the construction sector can apply it more in the future.

Plastics have polymers as the main content and these plastics can be formed by applying the proper pressure and temperature. So, there are various types and uses of plastic that can be found in the market until now. People choose plastic for their daily use because of its easy and simple use. Because of that, the percentage of plastic waste can be seen to be mostly from domestic sources. However, this plastic has a negative impact on the environment. Plastic is one of the most difficult materials to dispose of because it takes a long time for it to break down properly. Recycling is the most efficient method because the plastic waste will be reused in various ways. This study uses plastic waste in the building material which is concrete. Concrete is a mixture of cement, aggregate, and sand according to a certain ratio. All three of these materials are natural sources from the breaking of rocks in quarries and they consume large areas. Replacing plastic with aggregate can reduce the use of natural resources and save the environment. A study was conducted on both materials and a search for previous studies that used the material was also used as a reference. This study is very important to help produce sustainable products and reduce existing environmental pollution.

2. Methodology

2.1 Material

In this study, Ordinary Portland Cement (OPC) is used following the standard set by the Malaysian Standard MS EN 197-1: 2014 CEM I 42.5N. The aggregates used were coarse aggregate and fine aggregate. The coarse aggregates were sieved with a 10mm sieve according to the specifications set. All three materials were obtained from Makmal Kejuruteraan Bahan Termaju, Universiti Tun Hussein Onn Malaysia. Polyethylene terephthalate (PET) was used as a replacement material in concrete. The PET was collected at the recycling center at Pantai Minyak Beku, Batu Pahat and also the recycling center at Universiti Tun Hussein Onn Malaysia (UTHM). The collected bottles were cleaned from soiling and cut into two different sizes to replace the coarse aggregate and fine aggregate. Fig. 1 shows the two types of PET used partially replaced in the fine and coarse aggregate.

(a) (d)

(b) (c)

Fig. 1 *(a) PET used to partially replace fine aggregate (b) Fine aggregate (c) PET used to partially replace coarse aggregate (d) Coarse aggregate*

2.2 Concrete mix proportion

One of the objectives of this study is to identify the appropriate ratio of plastic, cement, aggregates, and water-cement ratio used in concrete. Therefore, this study utilizes the British Standard, specifically the Department of Environment's (DoE) method, to obtain suitable proportions for these materials. There are two design mixes calculated for their ratios: the first is the control mix, which represents the normal concrete mix, and the second is the design mix used in this study, which incorporates plastic as a partial replacement for fine aggregate and coarse aggregate . In total, there are five different concrete mixes, as shown in Table 1. These concrete mixes maintain water-cement ratio of 0.54, with a corresponding water weight of 213 kilograms per cubic meter. The replacement of plastic involves two different values, which are 10% annd 20%. The first condition involves replacing plastic with fine aggregate while keeping the coarse aggregate constant. Subsequently, the fine aggregate is replaced with plastic while maintaining the constant coarse aggregate. Each batch is named according to the replacement used.

Table 1 *Proportion of aggregates for concrete mixtures per meter cubic*

Designation of plastic (DP)	Water-cement ratio (w/c)	Replacement plastic (%)	Water (kg/m^3)	Cement (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	PET (kg/m^3)	No of Samples
DP0	0.54	0	213	394	956	847	0	6
DP10C	0.54	10	213	394	951	847	5	6
DP20C	0.54	20	213	394	946	847	10	6
DP10F	0.54	10	213	394	956	835	12	6
DP20F	0.54	20	213	394	956	823	24	6
							Total	30

Notes: DP0: control 0% replacement, DP10C: replacement 10% of coarse, DP20C: replacement 20% of coarse, DP10F: replacement 10% of fine, DP20F: replacement 20% of fine, PET: Polyethylene terephthalate

2.3 Concrete mixture

The preparation of concrete cube specimens for testing, based on the British Standard (BS), typically follows the guidelines outlined in BS EN 12390-1:2019. When preparing concrete cube specimens, it is important to select materials that accurately represent the desired mix design and production process while ensuring compliance with the relevant British Standards. Fig. 2 (a) shows a plastic concrete batch with a fine aggregate replacement. Subsequently, a mold made of a rigid and non-absorbent material such as plastic was used, and it was ensured that it was clean and free from any residual concrete or unfavorable material. To facilitate the removal of hardened specimens, the inner surface of the mold is carefully cleaned and a thin layer of release agent is applied. The desired sample reference size is 100mm x 100mm x 100mm. Therefore, only two layers of freshly mixed concrete of the same composition need to be poured into the mold, and each layer should be compacted using suitable equipment to remove and incorporate air leaks through 25 strokes of compaction. The surface of each layer is leveled using a trowel or float, ensuring a flat top surface free from irregularities. After the surface is flattened, each mold is labeled with the number of samples for each concrete mixed and the number of days of soaking in water. The mold samples were placed in a safe, room-temperature area according to the required British standard. After 24 hours, the concrete was carefully removed from the mold. In addition, the mold that has been used is cleaned and placed back in the place set by the laboratory. All 30 samples removed from the mold were cured for 7 and 28 days, 15 samples for 7 days curing, 15 samples for 28 days curing with different concrete mixtures (Fig. 2(b)).

(a) (b)

Fig. 2 *(a) Plastic concrete batch with a fine aggregate replacement (b) samples curing for 7 and 28 days*

2.4 Experiment

The five concrete mixes were mixed manually. Then, the fresh mixture was subjected to a slump test immediately to test the workability of the mix (Fig. 3 (b)). This process involves filling the moistened base, compressing it in layers, and measuring the slump as an indicator of workability according to the British standard BS EN 12350-2 (British Standard Institute, 2009). Density tests for hardened concretes follow the guidelines of BS EN 12390-7 and require measurements of the specimen's mass and volume, enabling calculation of the concrete's density (British Standards Institute, 2000). The water absorption test, conducted in accordance with BS EN 12390-7:2019, assesses the ability of concrete to absorb water by measuring the change in weight after a period of immersion (British Standards Institute, 2012). Finally, the compressive strength test, conducted to BS EN 12390-3:2001, assesses the load-bearing capacity of concrete cubes using a testing machine, assessing the type of failure and ensuring proper compliance (British Standards Institute, 2019). Each concrete mix has three samples to test and the concretes are averaged over the test values to obtain a more precise value (Fig. 3 (b)). These tests collectively provide an important insight into the quality, durability and performance of concrete in a variety of construction applications.

(a) (b)

Fig. 3 *(a) Slump test (b) Compressive strength test*

3. Results and Discussion

3.1 Slump test

The slump test is conducted to determine the workability and durability of the freshly mixed concrete. Based on the concrete mix design using the DOE method as in appendix A, the slump value should fall within the range of 30 to 60 mm. Based on Table 2 data, it can be concluded that all concrete mixes containing Polyethylene terephthalate (PET) have greater slump values than the control mix (DP0). The lower specific gravity of PET compared to both coarse and fine aggregates results in a reduced overall density for the concrete mix, thus increasing the slump value.

Furthermore, the size and shape of PET particles can affect the overall performance of the concrete mix. Smaller particles may show greater effectiveness in reducing friction and improving workability, while larger particles may have a more limited effect. In conclusion, studies demonstrates that using PET in concrete mixes with varying percentages of replacement for fine and coarse aggregates can influence slump test results, with the most significant increase in slump values observed for DP20F, the mix with 20% replacement of fine aggregate with PET. These findings align with the observations of previous studies (Sau et al., 2023). The effects of PET on slump values can be attributed to its lower specific gravity, its ability to serve as a lubricant within the concrete mix, and the size and shape of the PET particles.

Table 2 *Slump value of concrete grade 30*

No of sample	Slump Value (mm)
DP0	33
DP10C	45
DP20C	56
DP10F	48

DP20F	57

3.2 Density test

The density test results, presented in Fig. 4, reveal that the incorporation of plastic waste consistently led to a reduction in the density of concrete mixes. This finding holds significance for potential applications in lightweight concrete structures. Notably, all mixes containing plastic waste, including DP10C, DP20C, DP10F, and DP20F, exhibited lower density values compared to the control mix DP0, which have 0% plastic content. Furthermore, the extent of density reduction was observed to be greater in mixes with higher percentages of plastic replacement, as demonstrated by the lower density values recorded for DP20C and DP20F compared to DP10C and DP10F. Interestingly, mixes with fine aggregate replacement, namely DP10F and DP20F, demonstrated lower density values than those with coarse aggregate replacement, suggesting that the type of aggregate being replaced influences the resulting density.

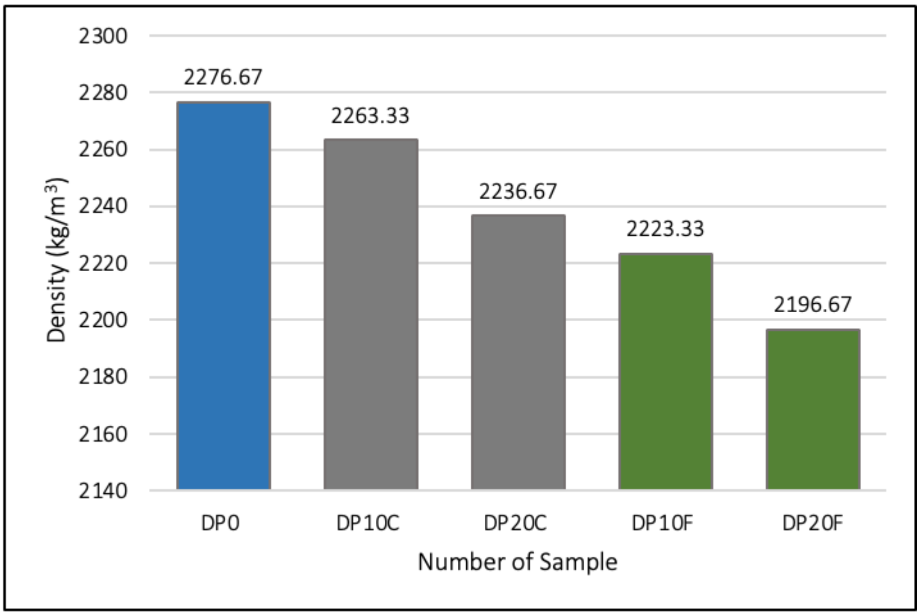

Fig. 4 *Comparison of densit (kg/m³) between replacement plastics in coarse aggregate and fine aggregate*

Several factors likely contribute to the observed density reduction. The lower specific gravity of plastic waste compared to traditional aggregates plays a key role. By partially replacing denser aggregate particles with plastic, the overall density of the concrete mix is reduced. Additionally, the presence of PET fibres within the plastic waste might further contribute to density reduction due to their relatively low specific gravity. The size and distribution of plastic particles within the mix could also influence density, potentially affecting air void content and particle packing. The impact of PET in concrete mix on density observed in this study parallels the results of previous studies (Almeshal et al., 2020; Islam & Shahjalal, 2021; Sau et al., 2023).

3.3 Water absorption test

In the present study, the water absorption properties of five different types of concrete mixes were analysed. This test is significant as it aids in assessing the durability and permeability of concrete. High water absorption can lead to various issues such as reduced strength, cracking and degradation time. The samples included a control sample (DPO) and samples with replacements of 10% coarse aggregate (DP10C), 20% coarse aggregate (DP20C), 10% fine aggregate (DP10F), and 20% fine aggregate (DP20F). The results revealed varying percentages of water absorption among the samples.

Based on Fig. 5, the control sample (DP0) which was cured for 7 days showed the moderate water absorption percentage of 1.90%. On the other hand, the samples with 10% coarse aggregate (DP10C) and 10% fine aggregate (DP10F) replacement had high water absorption rates compared to the 20% aggregate replacement (DP20C, DP20F). Between the 10% PET replacement of coarse and fine aggregates, DP10F has the highest absorption rate compared to DP10C. But when the replacement of PET is 20%, DP20C has a higher absorption rate than DP20F and it is higher than the control sample (DP0). So the suitable replacement rate in terms of water absorption and then soaked for 7 days is 10%. The patterns of data for concretes cured for 28 days are the similar to those of concretes cured for 7 days. A high resistance to water penetration is indicated by the very low water absorption rate of DP0. Higher water absorption by DP10F indicates an increase in opacity, while the lowest absorption by DP20F indicates a remarkable resistance to water infiltration.

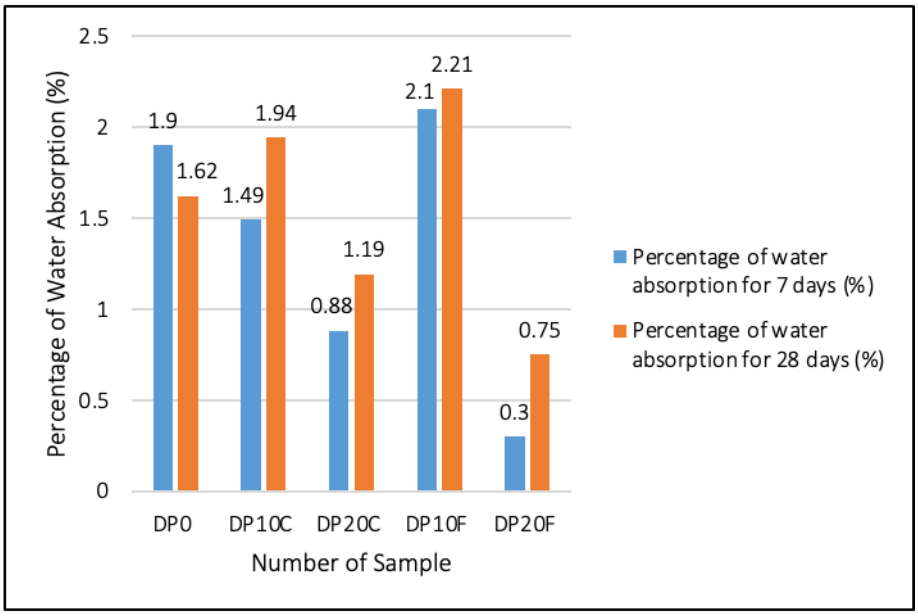

Fig. 5 *Comparison of water absorption percentage (%) of concretes cured for 7 Days with 28 Days*

In conclusion, Fig. 5 shows that the coarse aggregate replacement in increasing the water absorption capacity of concrete than the fine aggregate replacement method. In addition, the absorption percentage for concrete mixed with PET cured for 28 days is even higher than 7 days. The differences in water absorption among the samples can be attributed to various factors, such as the different compositions of the replacement aggregates, the degree of saturation, and the curing process. It is essential to consider these factors during the design and construction process to minimize any potential adverse effects on the performance and service life of the structures made from these concrete mixes.

3.4 Compressive strength test

Based on the data obtained in Fig. 6, the control sample (DP0) has the highest compressive strength, both for 7 and 28 days. This is because, the concrete mix was used as the control sample or reference sample for grade 30 for this study. Whereas, the concrete samples with coarse aggregate replacement (DP10C and DP20C) had slightly lower compressive strength values than the control samples but the compressive strength values at day 28 exceeded the target strength of grade 30 concrete. In addition, DP10C and DP20C at day 7 recorded target compressive strengths that were stronger than expected.

Furthermore, the concrete samples with fine aggregate replacement (DP10F and DP20F) had much lower compressive strength values than the control samples but PET DP10F concretes had much higher compressive strength values than DP10C and DP20C. The pattern of the results of replacing the fine aggregate is aligned with past research (Almeshal et al., 2020; Janardhan et al., 2023; Liu et al., 2022; Steyn et al., 2021) meanwhile, coarse aggregate had a similar pattern for a few past research (Islam et al., 2022; Islam & Shahjalal, 2021). The problem encountered for PET concretes with fine aggregate replacement is that the compressive strength value for 20% replacement (DP20F) does not exceed the target strength grade 30 for 7 days and 28 days.

The compressive strength of the concrete mixture depends on the type of replacement and the period after the mixing process. Concrete mixes with 100% natural aggregates provide the highest compressive strength, while replacement of fine aggregate with a higher percentage can result in a more significant reduction in compressive strength. The effect of replacement type on compressive strength is more significant during the initial stage after the mixing process compared to the period after 28 days. Furthermore, concrete with PET mixture cannot reach the compressive strength of the control sample (DP0). Therefore, the replacement of aggregates in concrete has its own percentage suitability and PET concrete cannot be intended as a concrete capable of supporting more loads than normal concrete.

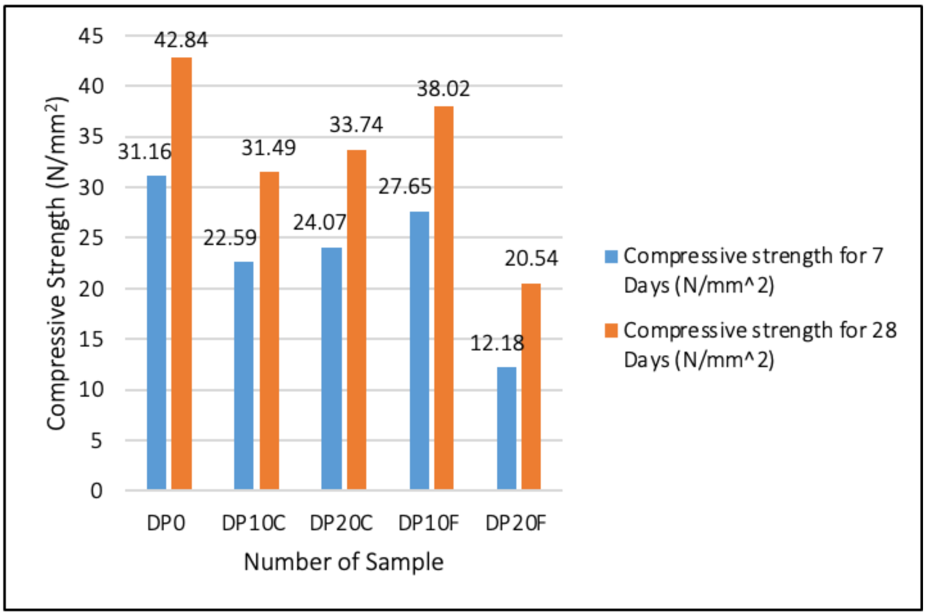

Fig. 6 *Comparison of compressive strength (N/mm²) of concretes for 7 and 28 days*

4. Conclusion

In conclusion, this study explores the effect of domestic plastic waste on various concrete properties, with a focus on its potential as a sustainable substitute for aggregates. Through several experimentation, involving different combinations of plastic, cement, aggregates, and water-cement ratios, the study identifies optimal mixtures and evaluates the influence of plastic waste on crucial concrete characteristics, including slump, density, water absorption, and compressive strength. Results indicate that incorporating Polyethylene terephthalate (PET) affects workability and reduces concrete density, potentially enabling the development of lightweight concrete with advantages in transportation and specific applications. Water absorption rates vary, with 10% PET replacement considered suitable, while compressive strength results emphasize the need for careful balancing of plastic replacement percentages for specific applications. These findings contribute valuable insights to sustainable construction practices, shedding light on the potential benefits and challenges of incorporating plastic waste into concrete mixes and guiding future research towards achieving a balanced integration of sustainability and structural integrity in construction.

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