UNIABUJA Journal of Engineering and Technology

https://ujet.uniabuja.edu.ng/

ISSN: 2714-3236 (Online); 2714-3228 (Print)

Volume 2, Issue 2, 2025; 440-448

Relationship Between Water Absorption and Compressive Strength in Concrete Incorporating Polyethylene Terephthalate (PET)

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Abstract

In recent decades, it has become more important to extend the service life of concrete structures by decreasing the rate of concrete degradation while solving major environmental issue. Adding plastic elements such as Polyethylene Terephthalate (PET) to concrete is a means of reducing rate of water absorption in concrete, which is one of the causes of deterioration in concrete. The addition of PET to concrete matrix is not only a means of improving its properties but a way of solving the environmental problem created by non-biodegradable nature of PET bottles, a nuisance in most landfill around the world. Therefore, this study aimed at determining the relationship between water absorption and compressive strength of concrete incorporating PET powder. Concrete cube specimens of 150 mm x 150 mm x 150 mm and 100 mm x 100 mm x 100 mm were cast using a mix ratio of 1:2:4 to test the compressive strength and water absorption rate respectively. PET powder was added in 0, 1, 3, and 5% by weight of cement and cured in water for 7, 14, 28, and 56 days. The result of this research showed that there exists a weak inverse correlation (0.44) between compressive strength and water absorption in concrete incorporating PET powder. Also, adding PET powder to concrete is capable of increasing its compressive strength by up to 9.4% and reducing its water absorption by as much as 200%. 3% PET was the optimal inclusion for both compressive strength and water absorption. In addition, using PET powder in concrete is an effective way of disposing a non-biodegradable waste, saving cost and turning waste to wealth.

Keywords: *Water absorption, compressive strength, polyethylene terephthalate (PET), concrete workability.*

1.0 Introduction

Polyethylene Terephthalate (PET) bottles are one of the wastes generated in various municipalities of the world. The disturbing thing about PET bottles is that they are non-biodegradable thereby could be seen on landfills, waste dumps and drains in most urban centers of the developing world, causing environmental nuisance. According to Ferdous *et al.* (2021), plastic of which PET bottles is inclusive constitutes about 8 - 12% of municipal wastes in cities around the world. The challenge is not abating with PET bottle volume in use expected to reach 513 billion litres in 2025 (Bajracharya *et al.*,2016). To solve this environmental menace, PET bottles is been incorporated in concrete production either in strips or granules, thereby saving cost and time (Moghadam *et al.*, 2009). This research seeks to utilize crushed and granulated PET bottles by incorporating it into concrete production. Although it has been shown that adding higher volume of PET into concrete production could negatively impact it, yet replacing the aggregates by up to 12.5% has the potential of increasing compressive and split tensile strength of concrete (Gurunandan *et al.*, 2020; Moosvi, 2020). Pawaskar *et al.* (2021) observed that there was an increase in compressive strength of concrete when waste PET bottles were used to replace up to 4% of its fine aggregate; further addition caused gradual reduction in the compressive strength. It was also opined that PET can be of help in arresting micro cracks in concrete due to its water tightness. The shape, size and texture of PET bottles strips and granules determine their effect on the resulting concrete. Adding between 5% to 10% of textured PET bottle as replacement for fine aggregate can increase the compressive strength and work-ability of the concrete (Nadimalla *et al.*, 2019). On water absorption, addition of 1% to 3% PET fraction is capable of making concrete mix more impermeable and less porous (Won *et al.*, 2010; Hannawi *et al.*, 2010)

While the effect of PET on compressive strength of concrete has been the focus of many researchers, the relationship that exist between the compressive strength and other properties such as water absorption rate is equally of interest. Ramezanianpour *et al.*, (2011) observed that there exists a strong relationship between water absorption and compressive strength in concrete generally. This correlation according to Sabbag and Uyanik (2018) is dependent on curing type and regime, they concluded that compressive strength reduces with increasing water absorption rate. According to Ye *et al.*, (2017) water absorption is directly related to aggressive ion diffusing into the micro-structure of the concrete which in turn impact on its compressive strength. Yuan and Jia (2021), compared the water absorption of concrete made with Polypropylene fiber (PPFs) of 0.06 mm in diameter and glass fibre. The concrete with PPFs had higher water absorption than the one with glass fibres, and the PPF-reinforced concrete was higher than the plain concrete when the volume content of PPF was more than 0.45%. Similarly, Medeiros Junior *et al.* (2019) concluded that compressive strength is inversely proportional to water/binder ratio in pozzolanic concrete which in turns is directly proportional to the water absorption by capillary and immersion. In hybrid steel polypropylene fiber reinforced concrete incorporating recycled aggregate, Ouni *et al.* (2021) found that irrespective of the fibre used, there exist a strong inverse correlation (R^2 >0.7) between water absorption and compressive strength; higher water absorption translates to lower compressive strength. The same inverse relationship between compressive strength and water absorption was also observed by Nanya *et al.* (2021), while Huang and Zhao (2019) established that the relationship was a linear one. The water absorption of concrete is affected by the fibre content and fineness. While the relationship that existed between compressive strength and water absorption has been extensively studied in plain concrete, the impact of PET addition on these physical properties in concrete is yet to be fully explored.

In this research, the relationship that exists between compressive strength and water absorption in concrete incorporating various percentages of PET was studied. Also, the impact of granulated PET bottles as an additive on the compressive strength and water absorption rate of OPC concrete was explored; the relevance of which is premised on the emerging demand for a more sustainable, reliable and cost-effective concrete which will be able to resist the damages caused by the infiltration of water.

2.0 Materials and Methods

2.1 Materials

2.1.1 Cement

Ordinary Portland cement was the main binder used in the production of the concrete samples. Cement manufactured by Dangote Cement Company conforming to BS EN 197-1:2000 was used for this research. The grade of the cement was 42.5R. Table 1 showed the properties of the cement used.

Table 1: Oxide composition of Dangote Portland Cement (Akanni *et al*., 2014)

Oxide	%	BS for OPC
CaO (%)	64.0	63.0 - 67.0
SiO_2 (%)	22.0	21.0-22.0
Fe_2O_3 (%)	5.2	3.5-6.0
Al_2O_3 (%)	5.6	6.0 - 8.0
Free CaO(%)	2.36	2.0
SO_3 (%)	1.59	1.5-3.0
MgO (%)	0.58	≤2.0

2.1.2 Polyethylene Terephthalate (PET)

The PET bottles were obtained from Ado Ekiti. The bottles were washed, dried and crushed into powder (figure 2) before use. PET is a polymer matrix of ethylene terephthalate monomers with alternating ($C_{10}H_8O_4$) units (Paladhi *et al.,* 2022). The chemical equation for PET is shown in figure 1. While its physio-chemical characteristics is as shown in Table 2.

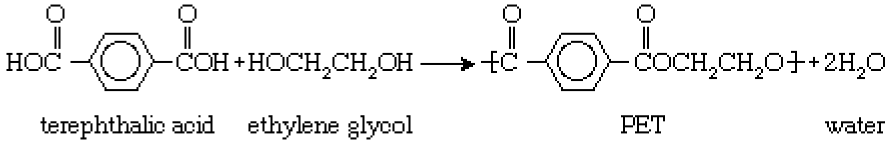

Figure 1: PET chemical Equation

Table 2. Physical and chemical properties of PET

Property	Value (Unit)
Molecular weight (of repeating unit)	192 (g mol^{-1})
Mark–Houwink parameters	k = 3.72 ·102 (ml g1) a = 0.73
Weight-average MW	30,000–80,000 (g mol1)
Density	1.41 (g cm^3)
Glass transition temperature	69–115 (°C)

Received: 04-05-2025 / Accepted: 11-06-2025 / Published: 30-09-2025
https://doi.org/10.70118/ujet.2025.0202.39

Property	Value (Unit)
Melting Temperature	265 (°C)
Heat of fusion	166 (J/g)
Breaking strength (Tensile)	50 (MPa)
Tensile strength (YoungÕs modulus)	1700 (MPa)
Yield strain (Tensile)	4 (%)
Impact strength	90 (J m1)
Water absorption (after 24 h)	0.5 (%)

Figure 2: PET powder

2.1.3 Silicone Sealant

During the water absorption test, silicone sealant was used as a water-resistant surface for the concrete cube specimens in this study. It usually has a gel-like appearance, texture, and behavior. Its chemical composition differs from that of conventional adhesives based on organic polymers. It was a choice because it is flexible and stable at both high and low temperatures.

2.1.4 Aggregates

The coarse aggregate used for this research was crushed granite with size of 4.75- 20 mm obtained from a quarry in Ikole, Ekiti State. The specific gravity was determined, and the sieve analysis was performed in compliance with BS 12620:2002. The fine aggregate used was natural fine sand graded to a minimum particle size of 0.150 mm and passing 4.75 mm sieve (conforming to BS 12620:2002).

2.1.5 Water

Water used for concrete should, at least, be drinkable, pure, and free of contaminants that could damage the material. Potable water from the Federal University, Oye concrete laboratory which conformed to BS EN 1008:2002 was used for the research work.

2.2 Methods

2.2.1 Mix Design

The mix ratio of 1:2:4 (binder: fine aggregate: coarse aggregate) in conformity with BS5328-2:1997 was used for the control and the PET concrete specimens. PET was absent from the control mix, as indicated in Table 3, but it was present in the other mixtures in varying amounts. Materials were mixed and batched in kilograms (kg). The concrete mixtures contained 1%, 3%, and 5% additions of PET powder. Ninety-six cubes of concrete were cast.

Table 3**:** Mix ratio for the concrete specimen

Designation	OPC (kg)	PET (kg)	Sand (kg)	Coarse Aggregate (kg)	Water (kg)
SPS 0	12.84	0	25.68	51.36	6.42
SPS 1	12.84	0.13	25.68	51.36	6.42
SPS 3	12.84	0.39	25.68	51.36	6.42
SPS 5	12.84	0.642	25.68	51.36	6.42

2.2.2 Mixing procedure

Various percentages of PET were added to the concrete based on cement weight. Before the cement was combined with the aggregates, the PET powder was added and mixed well to create a dry mix once the right water to binder ratio had been established. Fresh OPC/PET concrete was created by adding water to the dry mix and thoroughly mixing until it reached the desired consistency. Finally, the process was repeated for the different variations after the fresh concrete was poured into ready-made molds.

2.2.3 Casting and curing

Cube specimens of size 150mm x 150mm x 150mm were cast for the determination of compressive strength, while 100mm x100mm x 100mm were cast for the determination of water absorption rate. The concrete was mixed, placed and compacted in three layers. Compaction was done using tampering rod and the specimens finished with trowel. Following a 24-hour resting period, the specimens were demolded and stored in a curing tank for 7, 14, 28, and 56 days.

2.2.4 Compressive strength test

Compressive strength was determined conforming to BS EN 196-1 2005 on 150mm x 150mm x 150 mm concrete cube specimens. In accordance with the applicable criteria, the strength was calculated as the mean value of three specimens. The test apparatus which operate by lowering the top plate using a hydraulic ram to continuously place pressure on the cube specimen until failure. The following equation was used to determine the compressive strength.

$$\text{Compressive Strength (MPa)} = \frac{\text{Maximum Load (N)}}{\text{Cross−Section Area (mm)}} \quad (1)$$

2.2.5 Water Absorption Test

The water absorption test was carried out in accordance with ASTM C 1585. concrete specimens of 100 mm x 100mm x 100 mm were used. The concrete specimens were cured for the specified number of days, after which they were removed from the water and oven dried. The lower 50mm portion of each specimen was coated with silicone sealant as shown in figure 3 before placing it in a shallow layer of water as shown in figure 4 water for a period of 72 hours. The water absorption was determined using equation (2)

$$\text{Water absorption} = ((W_{ssd} - W_{od})/W_{od})*100 \quad (2)$$

where W_{ssd} is weight of saturated surface dry specimen and W_{od} is weight of oven dried specimen

Figure 3: Coating of concrete specimen with silicone

Figure 4: Concrete specimens inside water

3.0 Results and Discussion

3.1 Effect of PET on The Compressive Strength of Concrete

Irrespective of PET content, all concrete specimens gained strength as curing days increased from 7 through 56 days as shown in Figure 5. The specimen with 3% PET has the highest compressive strength of 18.1 N/mm^2 at 56 days while the specimen with 1% PET as well as the control specimen followed closely at 16.4 N/mm^2 and 16.47 N/mm^2 respectively at same maturity age of 56 days. The specimen with 5% PET has the least strength (15.73 N/mm^2) at 56 days of curing. The strength growth pattern of concrete with PET (7^{th} day strength was averagely 64% of the 28^{th} day strength) was also found to be consistent with that of the control specimen (7^{th} day strength was 61% of the 28^{th} day strength).

Received: 04-05-2025 / Accepted: 11-06-2025 / Published: 30-09-2025

https://doi.org/10.70118/ujet.2025.0202.39

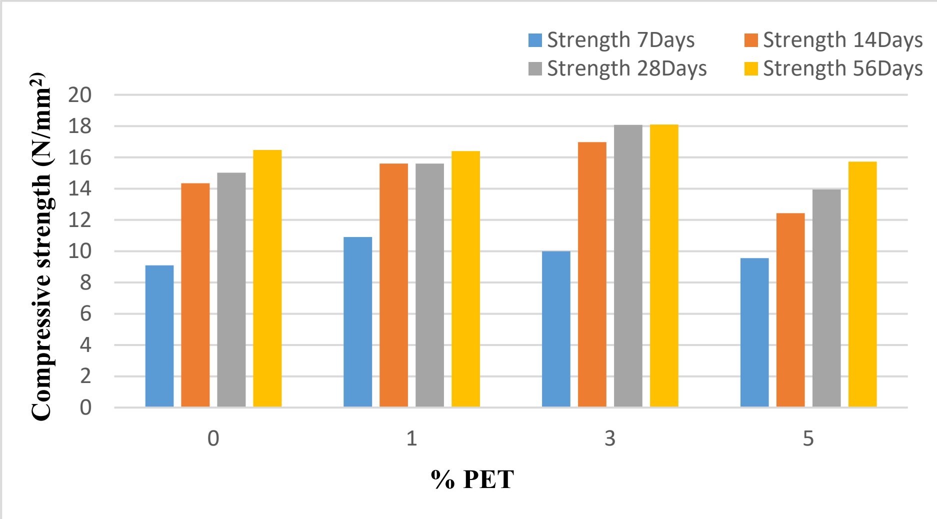

Figure 5: Compressive strength variation with progressing curing days

It was evident from the strength test results that the inclusion of PET further increased the compressive strength of the concrete specimens compared to the control specimens. From figure 6, the gradual increment in the percentages of PET content from 0% through 3% in the concrete specimen led to an increase in the compressive strength. By increasing the PET content from 3% to 5%, it was observed that the concrete specimens experienced drop in their compressive strength. The specimens with 3% PET were found to be 9.4% stronger than the control and 13% stronger than specimens with 5% PET. It was also discovered that compressive strength of specimen having 1% PET (16.4 N/mm^2) is almost the same with that of the control (16.47 N/mm^2).

This is an indication that anything below 1%, PET does not increase the strength of PET concrete. The impact of PET was more profound at 3%. It can therefore be concluded that PET can conveniently be used up to 3% in concrete production without fear of loss in strength. The reduction in strength at 5% PET inclusion was in agreement with the findings of Pawaskar *et al.*, (2021). The reason for the reduction in strength could be attributed to reduced bonding between the OPC binder and the aggregates. As the PET volume increased, the inter-phase created between the binder and the aggregate became weaker since PET does not possessed adhesive property.

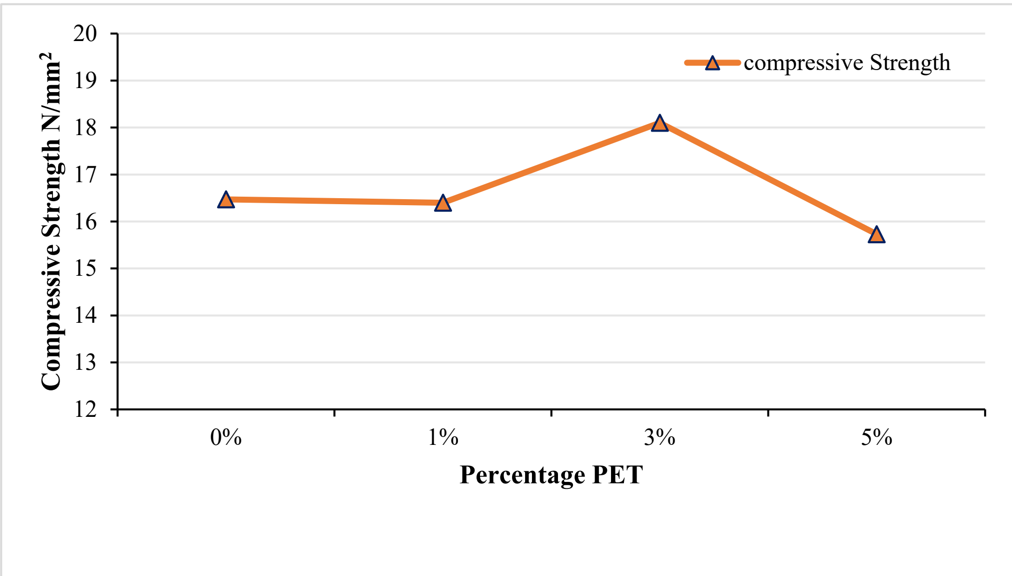

Figure 6: Average compressive strength variation with varying PET content

3.2 Effect of PET on Concrete Water Absorption Rate

Water absorption is the measure of water a concrete can absorb under the atmospheric pressure. For a durable concrete, the water absorption should not be higher than 6% (Tracz and Sliwinski, 2012). The water absorption in PET concrete ratios gradually decreased as the curing age increased. Generally, water absorption by the cubic specimens can be adjudged low, with all being less than 6% (Wilson and Tennis, 2021). The lowest percentage of water absorbed by the control specimen was 4.39% recorded at the 56^{th} day of curing

Received: 04-05-2025 / Accepted: 11-06-2025 / Published: 30-09-2025

https://doi.org/10.70118/ujet.2025.0202.39

while the highest was 5.51% on the 7th day. The effect of PET on the water absorption of concrete was found to be significant as shown in Table 4 (a value is considered significant when the T-Test value is less than 0.05). From figures 7 and 8, it was shown that with increasing PET content, the water absorption decreased for all the concrete samples examined. For the concrete with 1% PET the absorption decreased when compared to the control. The water absorption was 3.20% and 3.14% at 28 and 56 days respectively; which was 1.89% and 1.25% lower than that of the control at 28 and 56 days respectively.

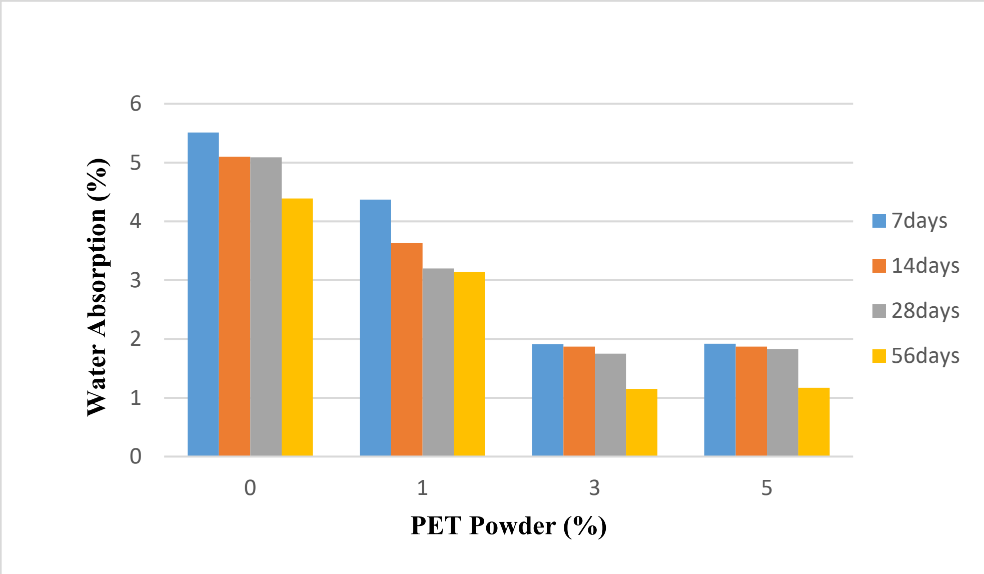

Figure 7: Water absorption for various PET content

Table 4: T-Test showing significance of water absorption rate

Significance mode	PET Content		
	1%	3%	5%
P (T<=t) two-tail	0.003200	0.000037	0.000042
P (T<=t) one-tail	0.001600	0.000019	0.000021

When compared to the water absorption of other PET ratios, the concrete with 3% PET content performed better, water absorption across all maturity ages showed significant reduction. The lowest absorption of 1.15% was recorded at the 56th day maturity, which was 3.24% lower than the water absorption of the control at the same age. Likewise, concrete with 5% PET content displayed a notable decrease in its absorption compared to the control. However, the absorption was still a little higher than that of 3% PET concrete. Figure 8 showed the average water absorption of concrete of various PET ratios with 3% PET concrete having the least water absorption of 1.67%. It could be concluded that, adding 3% to 5% PET content by weight of cement into concrete could significantly reduce its rate of absorbing water.

The reduction in water absorption as the PET content increased up to 3% optimum could be attributed to the packing of the capillary pores with PET which is not water soluble thereby reducing the porosity of the concrete. The water absorption started to increase from 5% PET inclusion due to reduced hydration of the concrete as a result of the increased PET content. Reduced hydration has been linked to porosity and increased water absorption in concrete. (Golewski, 2023)

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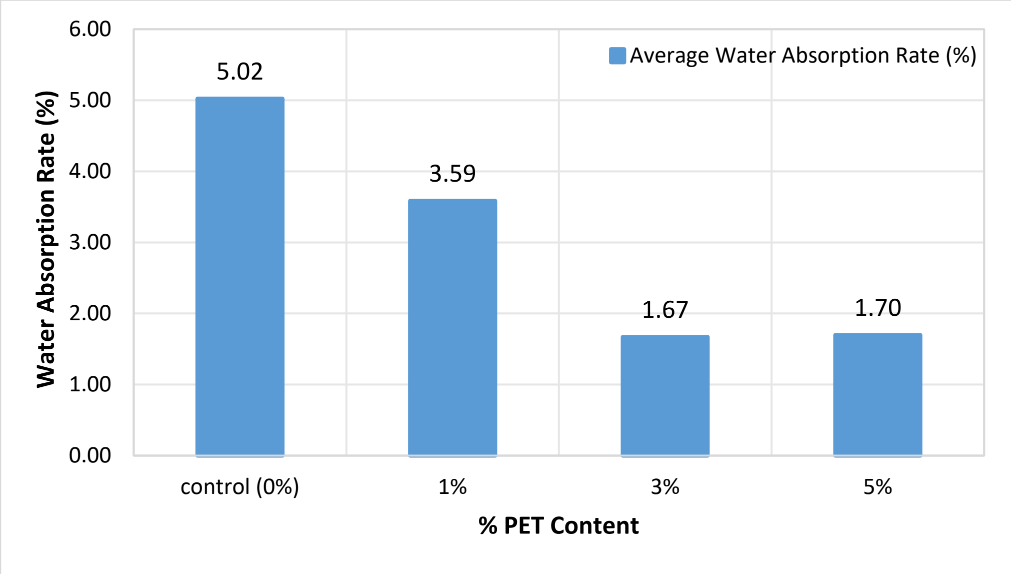

Figure 8: Average water absorption across all curing ages

3.3 Relationship Between Water Absorption and Compressive Strength

It was important to evaluate the correlation between compressive strength and water absorption in the PET concrete. From the trend-line in Figure 9, water absorption was shown to reduce with increased compressive strength. This observation as confirmed by Huang and Zhao (2019), Golewski (2023), and Medeiros-Junior *et al.,* (2019) showed that water absorption is inversely proportional to compressive strength. The 3% PET concrete which possessed the highest compressive strength also has the least average water absorption of 1.67%. The relationship between high compressive strength and low water absorption can be attributed to the dense micro-structure of the cement matrix as influenced by the optimum PET content and the possibility of PET acting as binder modifier.

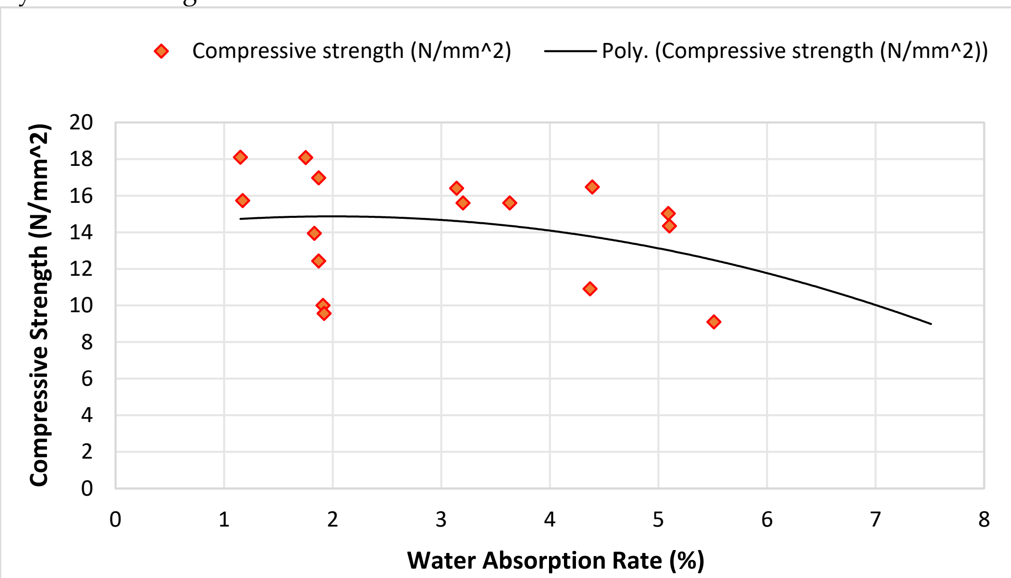

Figure 9: Relationship between Water Absorption and Compressive Strength

However, the fact that 5% PET concrete has a far lower water absorption of 1.17% and compressive strength of 15.73 N/mm^2 compared to the control's water absorption of 4.39% and higher compressive strength of 16.47 N/mm^2 indicated that there was no complete trenchant relationship between of water absorption and compressive strength in low PET concrete as also observed by Zhang and Zong (2014). The correlation value between water absorption and compressive strength was calculated as -0.44, this showed a weak inverse correlation between the two properties. From Figure 10, the low coefficient of correlation R^2 indicated that though the two properties are related, compressive strength cannot be simply explained by water absorption only.

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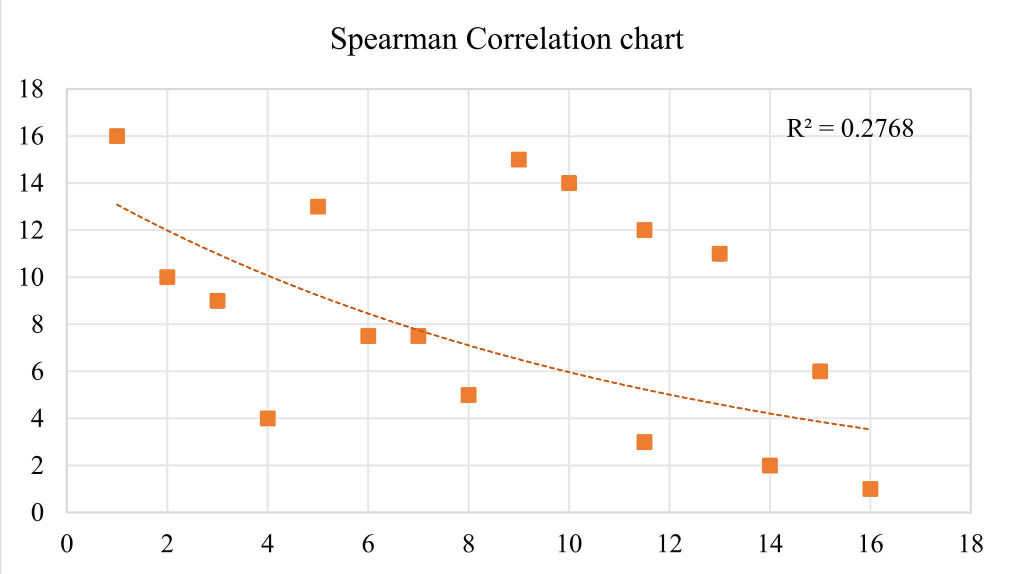

Figure 10: Correlation Plot between Water Absorption and Compressive Strength

4.0 Conclusion

The outcome of this research has demonstrated that the addition of PET powder can impact on the compressive strengths and water absorption of concrete. Concrete with PET exhibited increase in compressive strength relative to the control until 3% inclusion and reduction in compressive strength from 5% addition. Although concrete with 5% PET showed a decrease in its compressive strength as compared to the control, it was still within the acceptable strength for the mix design employed. The compressive strength reduction could be attributed to reduced hydration of the cement. The results of the water absorption test indicated that the addition of PET powder did lower the rate at which concrete absorbs water. The water absorption reduced with increasing PET addition up to 3%, this could be attributed to the packing of the capillary pores with PET granules in the concrete. It was observed that at 5% PET, water absorption increased marginally though it was still much lower than that of the control. Water absorption was also found to have a weak inverse relationship with compressive strength. In conclusion, to achieve the targeted compressive strength as well as low water absorption, 3% PET powder should be considered as optimum inclusion. This transformed to 200% reduction in water absorption. In addition, using PET powder in concrete is an effective way of disposing a non-biodegradable waste, saving cost and turning waste to wealth.

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