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EFFECTS OF POLYETHYLENE TEREPHTHALATE (PET) PLASTICS ON THE MECHANICAL PROPERTIES OF FLY ASH CONCRETE

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ABSTRACT: Concrete is the favored construction material for its high compressive strength and low maintenance cost. With the global interest in sustainable construction materials, continuous research is being done on alternative concrete materials. Research is geared toward the improvement of concrete properties as well as contributing to waste utilization. A study was conducted by incorporating polyethylene terephthalate plastics (PET) into fly ash concrete to investigate the effects on compressive and flexural strengths. As the addition of fly ash as a partial replacement for concrete is known to improve concrete strength, the addition of PET as a partial substitute for fine aggregates could be advantageous. A constant of 30% fly ash was used in the concrete mix proportions for test specimens, while the amount of PET introduced varied from zero to 15%. Specimens were prepared and tested following ASTM standards. It was observed that increasing the amount of PET in fly ash concrete mix also increased workability and decreased the unit weight of concrete. Compressive strength test results show that 5% to 10% PET plastic substitution increased the compressive strength of fly ash concrete. Test specimens containing 5% PET led to an increase in the flexural strength of fly ash concrete and a further increase in PET content indicated a decrease in flexural strength. The results of this study show that the inclusion of PET in fly ash concrete could lead to increased workability, a decrease in unit weight, and improved compressive and flexural strength without the use of admixtures.

Keywords: Fly ash concrete, Polyethylene terephthalate, Compressive strength, Flexural strength, Microstructure

1. INTRODUCTION

Concrete is one of the most common building materials used worldwide. It is a favored construction material owing to its high compressive strength and low maintenance cost. Numerous research on substitutable materials for cement as well as for both fine and coarse aggregates is continuously conducted to further improve concrete properties and contribute to waste utilization with the use of alternative concrete materials. Fly ash [1]- [3], palm oil fuel ash [4], and coconut shell ash [5] are some examples of viable substitutes for cement. Recycled solid wastes such as wastes from aggregate quarries have been found as a possible replacement for conventional fine aggregates [6].

It was anticipated that there would be numerous coal power plants will be constructed in the Philippines over the next five years to account for the electrical consumption needs of the country. The large power demand would then increase the amount of fly ash produced annually. The abundance of fly ash motivated researchers to investigate its effects on concrete properties. Studies have affirmed that the addition of fly ash can be beneficial to the mechanical properties of concrete. The incorporation of until 40% fly ash, as a partial substitute to cement, can increase the compressive and flexural strength of concrete as well as improve its stress-strain behavior [1], [2].

Polyethylene terephthalate (PET) plastic is one of the most heavily produced waste materials. However, only a small percentage of this waste is recycled leaving the rest dumped in landfills and oceans. Studies by Nikbin [7] and Jo et al. [8] indicated that PET plastics could be used as a partial substitute for fine aggregates in concrete, which resulted in lightweight concrete due to the reduction in unit weight. Borg [9] stated that PET plastics could cause insignificant changes in the strength of concrete if used in small percentages. Borg [9] suggested that partial substitution of PET plastics up to 8% without contributing significant detrimental effects on the compressive strength of concrete.

2. RESEARCH SIGNIFICANCE

A study on the combined effects of polyethylene terephthalate plastics (PET) and Class F fly ash (FA) as partial substitutes for fine aggregates and cement, respectively, on the mechanical properties of concrete was conducted. As previously stated, these waste materials continuously increase over time in landfills and bodies of water. This study aims to provide additional information for the field of civil engineering, and also contribute to the reduction and utilization of waste materials.

3. EXPERIMENTAL PROGRAM

To evaluate the combined effects of the substitution of PET plastics and Class F fly ash on the strength properties of concrete, alternative concrete mix proportions were generated following ACI 211.1 [10]. The amount of fly ash used as a partial substitute for cement was constant at 30 percent. The amount of PET plastics used to substitute fine aggregates varied from zero to 15 percent. The mix design used for test specimens is shown in Table 1, using a water-cement ratio of 0.50 and a target strength of 28 MPa for control specimens.

Table 1 Mix design used for tested samples

Component	0F-0P	30F-0P	30F-5P	30F-10P	30F-15P
Water, kg	184.0	184.0	184.0	184.0	184.0
Cement, kg	384.9	269.5	269.5	269.5	269.5
Sand, kg	722.7	672.8	639.1	605.5	571.8
Gravel, kg	930.0	930.0	930.0	930.0	930.0
Fly ash, kg	0	82.5	82.5	82.5	82.5
PET, kg	0	0	19.3	38.7	58.0

Note: F = Fly ash, P = PET

The compressive strength of concrete was investigated using cylindrical specimens of 150 mm in diameter and 300 mm in height and subjected to compression tests with a loading rate of 0.34 MPa/s per ASTM C39 [11]. The compressive strengths after 7, 14, 21, and 28 days were documented to compare the strength development between the different mix designs and to determine the effect of fly ash and PET plastics on the compressive strength of concrete. Beam specimens with dimensions of 150 mm x 250 mm x 500 mm were tested under the third-point loading condition following the procedure in ASTM C78 [11] to determine flexural strength. Strain gauges were attached to beam specimens to observe the stress-strain behavior of the samples. The flexural strength of the samples was determined at 28 days of curing to represent the theoretical maximum flexural strength of concrete. A total of 100 cylindrical specimens and 15 beam specimens were investigated.

Scanning Electron Microscopy (SEM) test was used to visually observe the chemical bonding of the materials used in the concrete mix. Samples for the test were randomly taken from the pieces used in the strength tests.

4. EXPERIMENTAL RESULTS

4.1 Physical Properties

The physical properties observed in the study were the workability and unit weight of fly ash concrete as these properties have been noted to be affected by the incorporation of PET plastics. The results are summarized in Table 2.

Table 2 Workability and unit weight of concrete samples

Concrete Mix	Slump, mm	Unit Weight, kN/m^3
0F-0P	81.25	22.38
30F-0P	82.50	22.14
30F-5P	90.25	22.01
30F-10P	95.25	21.85
30F-15P	103.50	21.67

Another notable observation was that the unit weight was affected by the incorporation of PET plastics in the fly ash concrete mix. As shown in Table 2, the unit weight decreased insignificantly when fly ash was incorporated into the mix. However, a sudden change in unit weight was noted when PET plastics were introduced. The largest decrease in unit weight was 5.14% with 15% PET plastic substitution. Results indicated that the unit weights were less than the typical normal concrete unit weight of 22 to 24 kN/m^3 but were still greater than 18 kN/m^3, which is the typical value for lightweight concrete. The decrease in unit weight was due to PET plastics being lighter than sand. The specific gravity of PET plastics was determined to be 1.33, which was almost half that of conventional sand used in concrete.

4.2 Compressive Strength

Table 3 presents the compressive strength at 28 days of the different mix designs tested. The control samples (0F-0P) surpassed the target strength of 28 MPa. As exhibited in Table 3, the addition of fly ash reduced the compressive strength of concrete while the incorporation of PET plastics increased the compressive strength of concrete.

Fly ash concrete samples (30F-0P) manifested a decrease of 17.14% in strength concerning the control samples. This was contradictory to previous studies stating that the incorporation of fly ash would increase the strength of concrete [7]. The reduction of strength could be attributed to the cement used in the study having substances such as fly ash already incorporated, which caused the fly ash composition of the cement to have gone over the optimum of 30%. Thus, also reducing the strength of concrete. PET plastics were observed to increase the strength of concrete compared to the samples with 0% PET plastics and 30% fly ash.

Table 3 Average compressive strength of tested samples after 28 days

Concrete Mix	Compressive Strength, MPa
0F-0P	29.12
30F-0P	24.13
30F-5P	26.05
30F-10P	26.73
30F-15P	24.73

Fly ash concrete samples with 5% PET plastics manifested an increase of 7.96% and samples with 10% PET plastics displayed an increase of 10.77%, both concerning the 0% PET plastics and 30% fly ash samples. Meanwhile, samples with 15% PET plastics exhibited a decrease in compressive strength. The decrease in compressive strength at 15% denotes that an increase in PET plastics would not contribute to a direct increase in strength. Rather, the trend suggests that PET plastics would be beneficial for the compressive strength of concrete only to a certain amount. With the trend manifesting in the study, the optimum PET percent is suggested to be between 5% and 15% PET plastic partial substitution for sand.

Regression analysis on the compressive strength results returned a polynomial function with an R^2 of 0.976 as shown in Eq. 1,

$$y = -0.0392x^2 + 0.6376x + 24.058 \qquad (1)$$

where: y is the compressive strength in MPa and x is the amount of PET plastics in percent. From Eq. 1, the amount of PET plastics that would generate optimum compressive strength of concrete with 30% fly ash was determined to be approximately 8.13%. Pearson correlation between theoretical and experimental compressive strength values per substitution of PET plastics up to 15% generated a linear relationship with an R^2 of 0.853 and R of 0.923. This indicated that the generated Eq. 1 was adequate to be used as a tool to estimate expected compressive strength up to 15% PET plastic substitution in concrete with 30% fly ash.

Figure 1 shows the strength development curve of the tested samples, which illustrated that PET plastics and fly ash do not significantly affect strength development as they simply manifest the same strength development trend as traditional concrete. The effect of PET plastics and fly ash on the compressive strength of concrete was seen to be significant through the Analysis of Variance (ANOVA). The analysis was performed with an alpha (α) value of 0.05. The F value of 9.04954 was greater than the critical F value of 2.8661. This indicated that the two materials (PET and FA) significantly affect the compressive strength of concrete. A P value (0.0002) less than the alpha value further strengthened the claim that the addition of PET plastics and Class F fly ash has a significant effect on the compressive strength of concrete compared to the typical concrete mix.

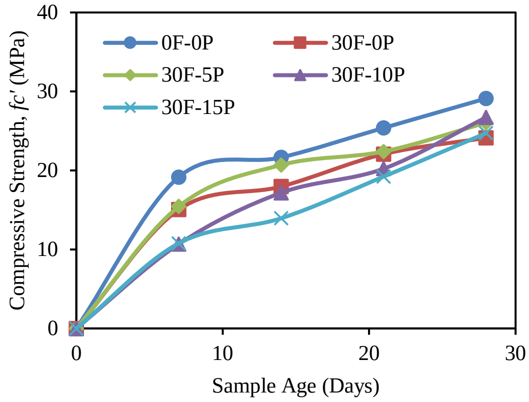

Fig. 1 Compressive strength development.

4.3 Flexural Strength

Table 4 shows the flexural strength of the samples tested in the study. As observed, the incorporation of fly ash reduced the strength of concrete likely because of the presence of fly ash in the cement powder causing a reduction in strength. On the other hand, the incorporation of PET plastics caused the concrete samples to have increased flexural strength. This result agrees with the observations made by Borg [9] wherein PET plastics were observed to sustain larger peak loads than control samples.

Table 4 Average flexural strength of tested samples after 28 days

Concrete Mix	Flexural Strength, MPa
0F-0P	2.40
30F-0P	2.08
30F-5P	2.98
30F-10P	2.52
30F-15P	2.47

A trend similar to the results obtained from the compressive strength test was observed in which the flexural strength of the concrete beams increased for partial substitution of 5% PET plastics. However, a drop was observed in flexural strength when partial substitution of PET reached 10%. Regression analysis of flexural strength was also conducted. The analysis returned a third-degree polynomial equation with an R^2 of 0.887 as shown in Eq. 2,

$$y = 0.0024x^3 - 0.0626x^2 + 0.4342x + 2.0777 \qquad (2)$$

where: y is the flexural strength in MPa and x is the amount of PET plastics in percent. From Eq. 2, it was determined that 4.78% PET plastics would produce optimum flexural strength in concrete with 30% fly ash. Pearson correlation analysis between the theoretical and experimental flexural strength of samples with PET plastics until 15% gave a linear relationship with an R^2 of 0.891 and R of 0.944. Similar to compressive strength results, the Pearson correlation analysis has shown that Eq. 2 was acceptable as a tool to estimate the expected flexural strength of concrete with 30 fly ash for PET plastic substitution of up to 15%.

Figure 2 illustrates the stress-strain graphs of the tested samples in the study. The incorporation of fly ash was observed to improve concrete stiffness, as the sample was able to sustain greater loads with less strain [12]. This was further supported by the modulus of elasticity values shown in Table 5 as samples with 0% PET and 30% fly ash having the greatest stiffness at approximately 30 GPa, as opposed to the control specimens with approximately 24 GPa. The result agreed with the results of the study of Uysal and Akyuncu [12] which claimed that fly ash may be used to improve the flexural performance of concrete due to its ability to increase the modulus of elasticity of concrete. In addition, fly ash concrete samples with PET plastics behaved like conventional concrete. However, the addition of PET plastics in fly ash concrete resulted in decreased stiffness. This can be attributed to the reduced frictional resistance between particles, as PET plastics are smooth and glassy in texture.

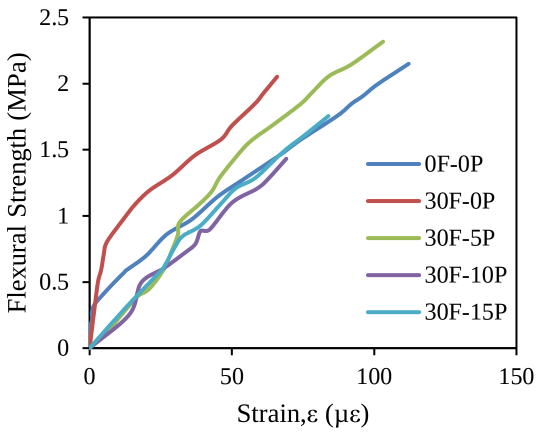

Fig. 2 Stress-strain curve of tested samples.

Results may show that PET plastics could be detrimental to the flexural behavior of concrete from the observed less desirable stress-strain behavior in the beams with PET plastics, in comparison to the samples with 0% PET and 30% fly ash. However, the detrimental effects were observed to be counteracted by the addition of fly ash. This compensation allowed samples with PET plastics to simply manifest similar deflection characteristics as the control samples. This indicated that the combination of PET plastics and fly ash can improve the flexural strength without negatively affecting the flexural behavior of concrete.

Table 5 Modulus of Elasticity of tested samples

Concrete Mix	Modulus of Elasticity, GPa
0F-0P	23.70
30F-0P	29.63
30F-5P	23.70
30F-10P	28.15
30F-15P	27.65

Similar to the effect of PET plastics on the compressive strength of fly ash concrete, the effect on flexural strength of concrete was also proven to be significant using ANOVA. The F value of 19.908 was seen to be much greater than the critical F value, 3.478, which verifies that the two materials did significantly affect the flexural strength of concrete. A P value less (9.407×10^{-5}) than the alpha value of 0.05 further strengthens the claim that the addition of PET plastics and Class F fly ash has an effect on the flexural strength of concrete compared to typical concrete.

4.4 Concrete Microstructure

The micro-fabric structure of the concrete samples was observed with the use of the Scanning Electron Microscope (SEM). The microstructure of the concrete in the SEM photographs was merely composed of sharp, angular, and flakey surfaces with smooth or rough textures. Smooth textured surfaces were identified as PET plastics, while grainy surfaces were recognized as concrete [13].

Figures 3, 4, and 5 show the microscopic view of fly ash concrete samples with 0%, 5%, and 15% PET plastics, respectively. Figure 3 shows the honeycomb-like pattern of plain concrete as well as the spherical particles, which indicate the presence of fly ash in the mix. The SEM image shown in Fig. 4 exhibits that the incorporation of PET plastics reduced the intergranular voids of concrete in comparison to fly ash concrete (Fig. 3). The reduction in intergranular voids manifests better bonding which then results in better strength. However, when the PET plastic substitution reached 15% (Fig. 5), the intergranular voids began to increase in size indicating weak bonding.

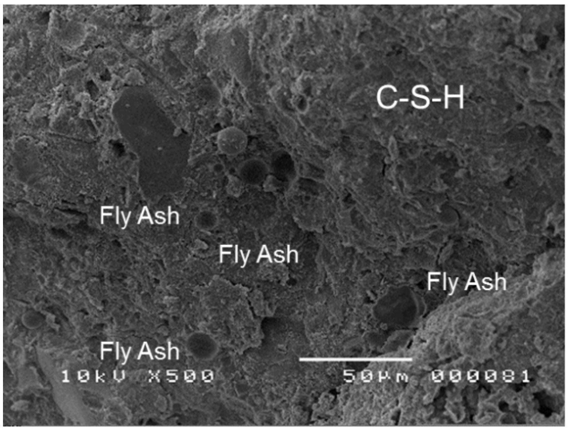

Fig. 3 SEM image of the 30F-0P test sample.

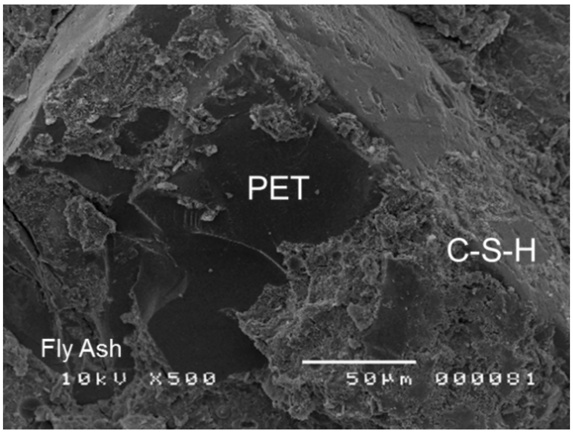

Fig. 4 SEM image of the 30F-5P test sample.

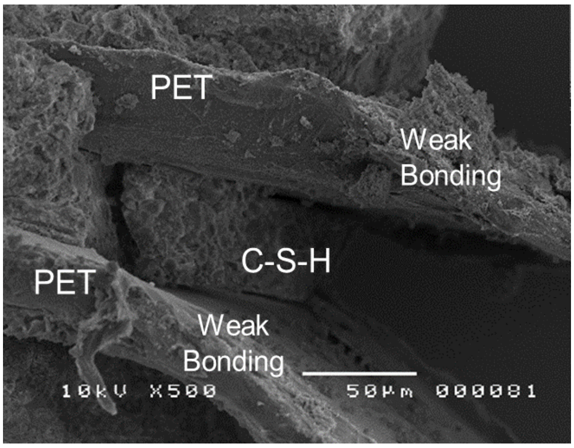

Fig. 5 SEM image of the 30F-15P test sample.

Figure 5 also shows that some of the parts of the PET plastic are no longer bonded to fly ash concrete. This weaker bonding could be the reason for the reduction of compressive and flexural strength in fly ash concrete with 10 to 15 percent PET plastics as was mentioned in the previous sections. It is possible that the increase in PET plastics (within the range of 10 to 15 percent) resulted in the reduction of calcium silicate hydrate (C-S-H) gel in the surrounding PET plastics within the concrete mix, thus leading to weaker bonding and reduced compressive and flexural strength.

5. CONCLUSION

The utilization of fly ash as partial cement substitute and PET plastics as partial fine aggregate substitute yielded noticeable effects on the performance of concrete and the following conclusions were made:

An evident increase in workability up to 27% was observed as PET plastic percentage increased. The incorporation of PET plastics into fly ash concrete also resulted in a 3.14% decrease in unit weight. Thus, PET plastics and fly ash produced concrete with higher workability with reduced unit weight.

Considering that the substitution of fly ash is constant within the other samples, it was observed that 5 and 10 percent of PET plastic substitution resulted in an increase in compressive strength of 8% and 11% from the control samples. Thus 5-10% of substitution of PET plastic promotes a beneficial increase in the compressive strength of concrete. The flexural strength of concrete was observed to increase with a 5% PET plastic substitution as compared to a 0% PET plastic substitution. It was evaluated to manifest a 43% increase in flexural strength. Thus, the addition of PET plastic will result in a noticeable increase in the flexural strength of the concrete.

Fly ash concrete with PET plastics from 10 to 15% has shown an increase in intergranular voids based on SEM images of tested samples. The increase in PET plastics resulted in the reduction of produced calcium silicate hydrate gel within the fly ash concrete mix. The lack of C-S-H gel created weaker bonds between the fly ash concrete and PET plastics and this led to the reduction of compressive and flexural strength.

Generated equations for predicting the compressive strength and the flexural strength of concrete with varying PET plastic percentages up to 15% were also verified to be valid and adequate with the use of external data obtained specifically for verification. Results indicate that a suggested amount of approximately 8.13% and 4.78% PET plastic substitution for fine aggregates in concrete with 30% fly ash would produce optimum compressive and flexural concrete strength, respectively.

The incorporation of both recyclable materials was observed to have no effect on the stress-strain behavior of concrete as well as the strength development of the concrete samples. With this, concrete with PET plastics and fly ash can be treated similarly to conventional concrete when used on-site in terms of strength development and in observing deformation behavior due to applied loads. Therefore, PET plastics and fly ash may be used as materials to increase both the compressive strength and flexural strength of concrete without affecting its stress-strain behavior.

PET plastics are a viable substitute for fine aggregates up to 10% substitution with 30% fly ash as cement replacement in the concrete mix without compromising the strength and quality of concrete products. However, it is recommended for further study on the long-term behavior of hardened concrete especially when it is exposed to elevated temperature. It is also recommended to investigate the compressive and flexural strengths of concrete with fly ash at a lower percentage and PET plastics higher than 10%.

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