

PERFORMANCE OF CONCRETE MIXED WITH FLY ASH AND PLASTIC WHEN EXPOSED TO FIRE

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ABSTRACT: Due to the negative environmental impacts of concrete production, several studies have explored other concrete materials, specifically plastic aggregates and fly ash. However, previous studies have focused on evaluating the alternative concrete for its strength properties and none for its performance during extreme events, such as a fire. Thus, this study sought to further validate the feasibility of alternative concrete by investigating its strength properties in conjunction with its post-fire performance. The concrete specimens were made by replacing sand with HDPE pellets by volume of fine aggregates, and cement with class F fly ash by weight of the binder. The parameters investigated were Compressive Strength (F_c'), Post-Fire Relative Residual Strength (RRS), and Fire Resistance Rating (FRR). The compressive strength tests were done on cylindrical specimens at varying curing periods (7,14,28, and 120 days), while fire performance tests were done on specimens cured for 28 days. The specimens were fired on one surface in a small-scale furnace. The fired cubes were then tested for compressive strength to obtain the RRS. The results show that to have comparable or increased strength than conventional concrete. Using the optimization model, response surface method, the optimum mix was garnered. This study is a stepping stone towards acceptance of the alternative concrete in the Philippines.

Keywords: Plastic, Fly Ash, Fire, Post-Fire Performance, Philippines

1. INTRODUCTION

The Philippines is considered one of the developing countries and, currently, one of its priorities is to develop its infrastructure, thus, it is noticeable that more projects are being constructed. More construction project entails more concrete is being used. Concrete is among the widely used structural materials due to its versatile properties, however, it has a negative environmental impact due to the production of some of its components, such as cement. Cement production is energy-intensive and emission-intensive because of the amount of heat needed during manufacturing. Moreover, the production of a ton of cement requires 4.7 million BTU of energy or 400 pounds of coal, which has an effect on the environment [1].

Many studies have been conducted locally in the use of waste materials as a substitute for some of the construction materials [2-8], such as fly ash. An option towards more sustainable concrete production is replacing energy-intensive cement with Supplementary Cementitious Materials (SCM) that are industrial by-products. Apart from economic and environmental benefits, SCMs enhance the strength and durability of concrete [9-11]. Being comprised of cement and aggregate, both of which containing inert materials, concrete is virtually non-combustible [12]. However, despite such attributes, concrete exposed to elevated temperatures still undergoes significant changes in its mechanical properties. Also, the

inclusion of fly ash in the concrete mix can improve the performance of concrete at elevated temperatures or its fire performance [13].

Aside from fly ash, another way to make concrete more sustainable is by substituting natural aggregates with less energy-intensive and sustainable materials, such as plastic. Currently, a growing number of researches have examined the feasibility of using waste plastic in concrete. Different plastic types have been investigated for their feasibility as aggregate, fiber, or filler for concrete, including Polyethylene Terephthalate (PET), Polyvinyl Chloride (PVC), High-Density Polyethylene (HDPE), Low-Density Polyethylene (LDPE), Expanded Polystyrene (EPS), Glass-Reinforced Plastic (GRP), Polycarbonate (PC), and Polypropylene (PP) [14]. In this study, the focus is on using HDPE as fine aggregates. This is due to the limited number of studies on that type as compared to PET and EPS, as well as the vast usage of HDPE in the Philippines.

In light of these two approaches towards sustainable concrete material, the researchers recognized that there is a gap in the current studies. Most published literature on the use of HDPE as fine aggregates has dealt with testing the mechanical properties only. Little has been done to assess other properties.

Based on the 2015 Annual Accomplishment Report of the Bureau of Fire Protection, fire incidents in the country increased from 15,879 to 17,138, where 8,501 were related to structural fires. Estimated

property damage of 3.62 billion was reported in the same year. Additionally, in 2012, the annual worldwide economic and human costs of fire-related casualties were estimated to amount to billions of dollars due to damaged property. Though no recent fire has been classified as a disaster, fire makes structures dangerous to public welfare due to hazards posed by structural failure, which is caused by the weakening of its materials. This has led to numerous efforts such as emergency responses and disaster risk reduction, but these may still not be enough to reduce the unpredictable effects of fire. As such, the disastrous impact of fire on livelihood and properties poses the need to investigate the fire resistance of concrete as the structural material.

As one of the primary objectives, the study evaluated the fire-resistance rating of alternative concrete. With the intended use as non-load bearing exterior walls, the specimens were not loaded during fire testing and only one face was exposed to fire. To save on material while still enabling comparison with the standards, the fire-resistance rating was determined for an effective wall thickness of 50 mm only, which has a standard fire rating of 30 minutes [15].

The researchers sought to integrate the growing body of knowledge from the two approaches in promoting concrete's sustainability, with the ultimate goal of producing a structural material that maximizes the use of waste materials without compromising its fire resistivity and strength. Since the addition of fly ash has been proven to enhance the fire performance of conventional concrete, it was anticipated that it would improve the fire resistance of the alternative concrete, thus permitting a higher plastic percentage replacement while still having an acceptable fire resistance and strength.

By determining the fire-resistance rating and post-fire residual strength of the concrete, the researchers were able to assess the fire performance of the alternative concrete as compared to conventional concrete. This provided information on the effects of fire on the structural integrity of this alternative material. Since the risk of fire is inevitable in any structure, studying the fire performance of building materials is relevant in the present and the future. The investigation of these properties is valuable in ensuring the safety of occupants in concrete structures and progressing towards sustainable concrete production.

The results lay the groundwork for future studies that aim to improve the performance of the alternative material. These add to existing literature that investigated the feasibility of concrete with HDPE aggregates, and of using fly ash to improve fire performance. It served as a stepping stone towards accepting HDPE concrete as a building material, particularly in the Philippines where fire incidence is high. The goal of reducing plastic waste and the

negative impacts of fire on structures was also fulfilled.

2. METHODOLOGY

The study dealt with the investigation of the strength performance of concrete with fly ash and recycled HDPE plastic aggregates through an experimental method of research. This was done by assessing the effect of varying amounts of substitution of fly ash and HDPE on the compressive strength of the concrete and fire performance.

There were 2 independent variables: the percentage of HDPE substitution and the percentage of fly ash substitution. The percentage of HDPE substitution were 0%, 5%, 10% and 15% by volume of fine aggregates. The level of substitution cannot be increased further due to the adverse effect of HDPE on the compressive strength of concrete.

Second, the percentages of fly ash substitution were 0%, 30%, and 60% by weight of the total binder. From past studies on concrete, fly ash was found to increase the residual strength of concrete at high levels of substitution – ranging from 20% to 60% by weight of the binder.

The main parameters that were investigated in this study were the Compressive Strength (F_c'), Post-Fire Relative Residual Strength (RRS), and the Fire-Resistance Rating (FRR). Cylindrical specimens with a 100 x 200-mm dimension were tested for compressive strength after curing for 7, 14, 21, 28, and 120 days. For the fire performance, 50-mm cube specimens that were cured for 28 days were tested for compressive strength, while a corresponding mix subjected to fire exposure was used to determine RRS and FRR. The results with and without fire exposure were compared to evaluate the relative strength loss. The specifications of the materials used are shown in Table 1.

With 2 independent mix design variables, fly ash and HDPE percent substitution, at 3 and 4 levels, respectively, giving a total of 12 types of mixes.

The preparation of the samples was divided into 3 batches based on the amount of fly ash substitution (0%, 30%, 60%). The concrete specimens were mixed and cast following ASTM C192 and ASTM C39 in the form of 100 x 200-mm cylindrical specimens and 50-mm cube specimens. After 24 hours of being cast, the specimens were removed from the molds and placed in a water bath at room temperature.

2.1 Compressive Strength

The cylindrical specimens were used to assess the compressive strength of the alternative concrete. Before placing in the cylindrical molds, the freshly mixed concrete was tested for the slump following ASTM C143, and adjustments were made to achieve

a workable concrete mix. The hardened concrete was tested for their compressive strength following ASTM C39, at different curing days, namely, 7, 14, 21, 28, and 120 days. The 28th-day strength was the basis for assessing the effect of the substitutions on the compressive strength of concrete.

Table 1 Specifications of Materials Used

Gravel	Gravel from Montalban, PH with max. size of 19 mm.
Sand	Natural sand from Pampanga, PH.
HDPE Plastic Pellets	Pellets approx. 3 mm in length and diameter, recycled from various HDPE products like post-consumer plastic.
Cement	Cement Type 1P Portland Cement
Fly Ash	Class F Fly Ash. As per ASTM C618, Class F has pozzolanic properties, less than 5% of CaO and more than 50% of SiO ₂ +Al ₂ O ₃ +Fe ₂ O ₃ .
Water	Clean tap water.

2.2 Fire Resistance Rating

For the standard fire tests, the 50-mm cubes were used. After curing for 28 days, the cube specimens underwent fire testing in a small-scale test furnace, as shown in Fig.1. The specimens were placed in the furnace starting from ambient temperature and heated through the ASTM E119 time-temperature curve. With a thermocouple attached to the unexposed surface of the specimen, the temperature of the specimen was monitored until the temperature was 139°C greater than the initial temperature, signifying the end of the test. This time in minutes was taken as the Fire-Resistance Rating (FRR) of the specimen. Afterward, the specimen was taken out from the furnace to cool for 24 hours at room temperature before undergoing compression testing.

During the fire resistance test, physical observations were noted during and after the test. This includes hearing any explosive spalling of the samples during the test and investigating the physical appearance of the fired samples, such as the occurrence of cracks and shrinkage.

2.3 Optimization

Further analysis was made through the graphs of the strength development, fire-resistance rating, and the individual effect of each substitution on the response variables. To find the optimum amount of percent substitutions, the Response Surface Method (RSM) analysis was carried out. A response surface

model equation was developed for each response variable.

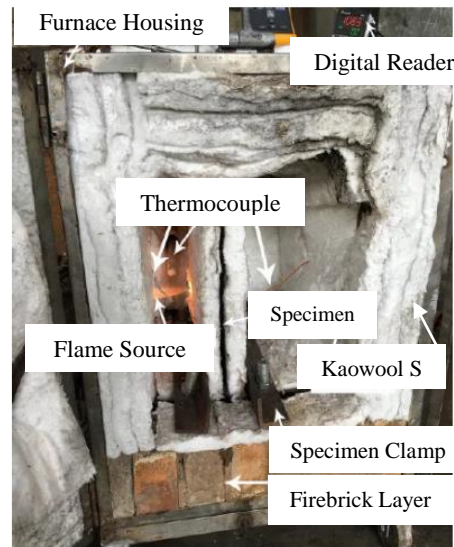


Fig.1 Small-scale furnace for fire testing [16]

3. RESULTS AND DISCUSSIONS

3.1 Compressive Strength Tests

A large portion of the concrete strength developed in the first 14 days of curing, ranging from 12.95% to 54.65% increase from 7th-day strength, the data is shown in Table 2. It was observed that the concrete with higher fly ash content had a higher percentage increase in the strength after 28 days. The addition of fly ash improved long-term strength. The rate of strength increase of Portland cement concrete slows down, the opposite happens to fly ash concrete due to the continued pozzolanic reaction with water in the later ages.

Table 2 Compressive strength of the specimen

MIX	Compressive Strength, MPa				
	7	14	21	28	120
0F-0H	29.65	33.49	34.02	34.20	34.38
0F-5H	15.69	18.41	20.91	28.57	28.63
0F-10H	23.69	34.87	38.52	38.60	38.89
0F-15H	23.76	27.48	31.14	30.89	31.32
30F-0H	20.42	27.91	31.76	33.73	34.34
30F-5H	15.76	21.43	26.79	27.09	28.19
30F-10H	13.54	19.16	21.00	24.92	26.47
30F-15H	14.41	20.68	22.29	22.91	25.40
60F-0H	8.22	12.71	17.17	17.39	19.94
60F-5H	10.48	14.75	17.82	20.50	22.45
60F-10H	8.06	11.77	16.03	17.54	19.79
60F-15H	9.40	14.08	16.96	20.47	21.95

It is possible that the strength of the 30F and 60F samples may still increase significantly beyond 120 days.

Concrete cylinder samples with 60% fly ash show failure in columnar vertical cracking from top to bottom of the concrete, the crack started from the top cap down to the bottom cap without forming well-defined cones on either end. With concrete samples that fail due to shearing means that the concrete is likely to have a high sand content.

0F, 30F-0H and 30F-5H samples characterized as a failure with side fractures are visible at the top. This failure pattern occurs commonly in samples subjected to compression tests with unbonded caps, which is the case for this study.

It can be observed that as the percentage of fly ash substitution increases, the failure pattern is more severe. For samples with no fly ash substitution, the failure is only caused by the unbonded caps used in the compression test. Hence, there is a strong bond between the aggregates. For samples with 60% fly ash substitution, the failure pattern illustrates a columnar failure, similar to a system of continuous parallel cracks in the direction of compression.

Replacing cement with fly ash had an adverse effect on the 28th day compressive strength, regardless of the HDPE content. Since the graph displays the 28th-day compressive strength which is considered early strength, this trend is consistent with the study conducted by Johari et. al (2011), where fly ash was found to reduce the early strength of concrete but improves the long term strength.

3.2 Relative Residual Strength (RRS) and Fire Resistance Rating (FRR)

The Relative Residual Strength (RRS) represents the remaining strength after fire exposure, relative to equivalent unfired samples. The fire-resistance rating is the time before failure as defined in ASTM E119. It represents how fast the heat can conduct through the concrete. The results are shown in Table 3.

Table 3 Relative Residual Strength (RRS) and Fire Resistance Rating (FRR) Results

Mix ID	RRS, %	FRR, min.
0F-0H	77.07	15.75
0F-5H	81.88	6.28
0F-10H	66.12	8.66
0F-15H	86.2	9.49
30F-0H	52.36	12.16
30F-5H	70.83	10.64
30F-10H	82.74	8.38
30F-15H	64.77	10.68
60F-0H	47.22	9.28
60F-5H	70.23	15.06
60F-10H	62.96	15.28
60F-15H	53.59	9.05

Minimum	47.22	6.28
Maximum	86.2	15.75

According to the International Building Code (2012), the standard fire-resistance rating for 50-mm thick concrete specimens is 30 minutes. The FRR that was attained in the test was only half of this value (15.753 minutes). A possible reason for this low value is due to the smaller scale testing equipment that was used. Since the test furnace has already been used several times since its fabrication, the quality of the results could not have been as accurate as of its initial testing.

For concrete with 0% HDPE, only charring occurred and surface spalling was negligible.

However, for concrete with 5% and 10% HDPE, there was a small part that melted away. For concrete with 15% HDPE, there was a significant reduction in the size of the concrete, and a large part of the cube was burnt.

It can be inferred that the surface spalling of concrete depends on the amount of HDPE. The higher the HDPE content, the more concrete was melted or stripped off. This was probably due to the melting of the plastic pellets that comprise the concrete matrix. Since the furnace temperature was observed to reach 400-600°C at failure, this was sufficient to melt the HDPE

The effect of fly ash on the RRS was quite similar to the effect on f_c' . All mixes except for the 10H samples decreased in RRS when fly ash replacement was increased from 0% to 30%. By contrast, the 10H mix had a peak RRS at 30%. Notably, all combinations decreased in RRS at 60% fly ash substitution. Overall, the fly ash negatively affected the concrete except for 10H samples which benefited from 30% fly ash substitution.

For the 0H samples, increased fly ash substitution resulted in a decrease in FRR. It was at its highest when no fly ash was present in the mix. It was the opposite of the 5H and 10H samples, where increased fly ash resulted in a higher fire-resistance rating.

Although the 5H samples attained a greater FRR at 30F, both 5H and 10H samples obtained similar FRR at 60F. For the 15H samples, however, the fly ash content did not significantly affect the FRR.

Overall, the control concrete attained the highest FRR, and adding fly ash to the 0H concrete adversely affected the FRR. However, when the concrete was mixed with HDPE at 5% and 10%, the fly ash improved the FRR of the alternative concrete.

In light of both the RRS and FRR, it appears that the 30F-5H and 60F- 5H samples were the best performing alternative mixes in terms of fire performance.

3.3 Response Surface Methodology

One of the main objectives of this study was to

build a model that would be useful in predicting the compressive strength, given the mix proportion of HDPE and fly ash as well as finding the optimum mix proportions for a given response criterion. Shown in Figs.2-4 are the 3D-surface plots generated for the Compressive Strength (f_c'), Post-Fire Residual Strength (RRS), and Fire Resistance Rating (FRR), as a function of the percent substitution of FA and HDPE.

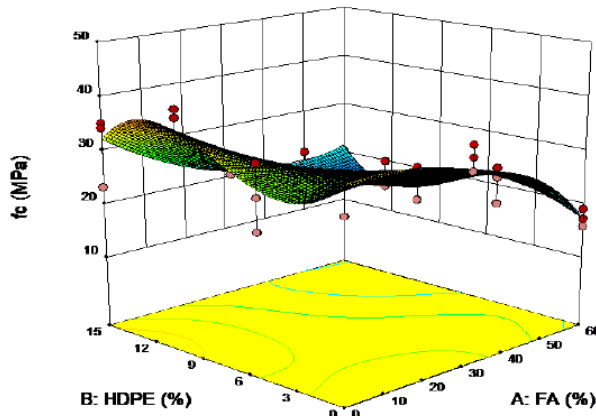


Fig.2 3D surface plot showing the 28th-day Compressive Strength as a function of fly ash and HDPE percent substitution

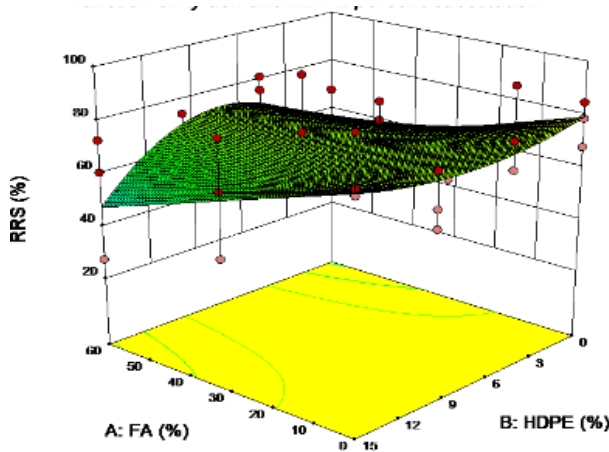


Fig.3 3D surface plot showing the Relative Residual Strength as a function of fly ash and HDPE percent substitution

Different models were investigated, but based on the adjusted r-squared, the quadratic model was found to be the most suitable. The backward elimination analysis was used to increase the precision of the model.

Before proceeding to optimization, the fitted models were examined to ensure that they give sufficient approximation of the results obtained in the experimental conditions.

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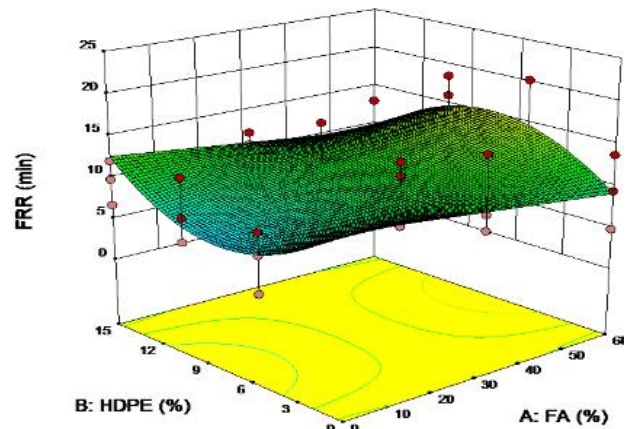


Fig4 3D surface plot showing the Fire-Resistance Rating as a function of fly ash and HDPE percent substitution

3.4 Validation

The actual and predicted values of the responses obtained using the three model equations are graphically presented in Figs.5a-5c, where the predicted values were plotted against the actual values later and a 45-degree line was used as a reference of equality between the two values [17-18].

It could be noted that due to the large variation in the responses for the RRS and FRR, the predicted values may be far off some of the actual values, which explains the low adjusted R-squared values. In Fig. 5a-5c, this was illustrated by the scattered behavior of the values around the equality line. For the f_c' , the points lied close to the equality line, which means the model has high accuracy in predicting the f_c' .

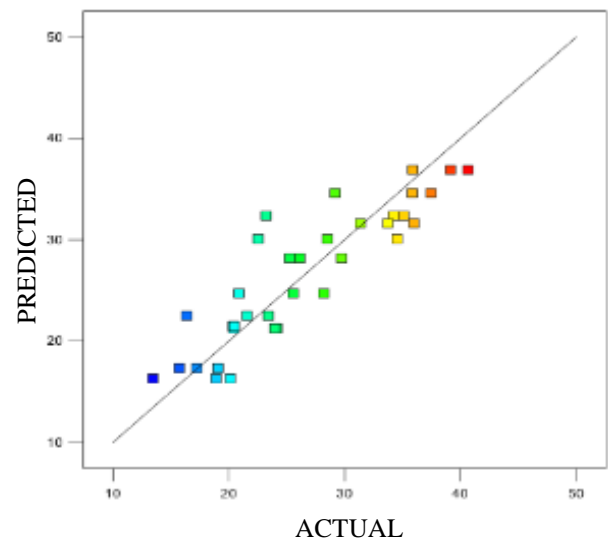


Fig.5a Predicted vs. actual plots of Compressive Strength

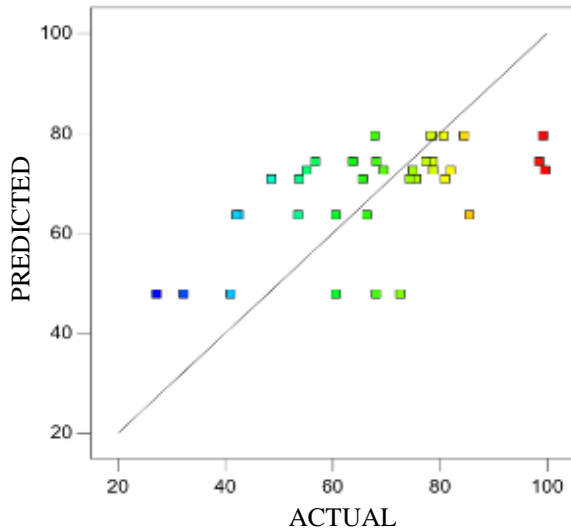


Fig.5b Predicted vs. actual plots of Relative Residual Strength

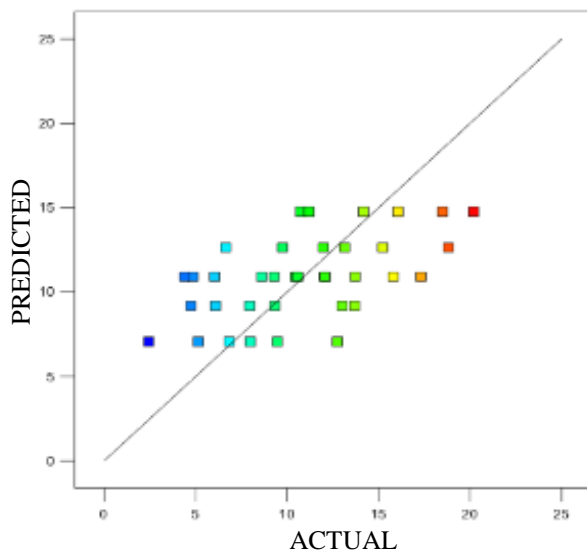


Fig.5c Predicted vs. actual plots of Fire-Resistance Rating

4. CONCLUSIONS

The majority of the concrete strength development occurred in the first 14 days of curing, with percentage increases relative to 7 days ranging from 12.95% to 54.65%. After 28 days, concrete with higher fly ash content showed a higher rate of increase due to delayed pozzolanic reaction of fly ash with water. The control concrete exceeded the target compressive strength of 25 MPa with an average strength of 34.20

MPa. Among the alternative concrete mixes, 0F-10H attained the highest strength with 38.60 MPa while 60F-0H attained the lowest strength with 17.39 MPa. HDPE as fine aggregate replacement slightly

increased or did not have a significant effect on the strength. This may be attributed to the size of the HDPE pellets which were larger than sand - thus leading to a strength increase despite their lower density. By contrast, fly ash as cement replacement decreases the strength, which was consistent with previous studies that observed Class F fly ash to be detrimental to the 28th-day compressive strength.

Cubes with 60% fly ash substitution were observed to be vulnerable to explosive spalling, whereas cubes with higher HDPE content were more vulnerable to surface spalling, as exhibited by a large reduction in size after fire exposure. Replacement of up to 5% HDPE increased the RRS. By contrast, fly ash generally decreased the RRS except for 10H samples which increased at 30% fly ash. At HDPE levels of 5%, 10%, 15%, the peak RRS was at fly ash levels of 60%, 30%, and 0%, respectively. It was surmised that at higher HDPE content, lower fly ash content was more favorable for the RRS. The control concrete attained the highest FRR with 15.75 minutes. Among the alternative concrete mixes, the 60F-5H and 60F-10H performed best with 15.06 minutes and 15.28 minutes, respectively. Similar to the RRS, the effect of fly ash on the FRR varied according to the HDPE content. Generally, the fly ash improved the FRR of 5H and 10H samples, while decreased those of 0H samples and did not affect those of 15H samples.

Using the response surface method, model equations were developed for use in predicting the compressive strength, relative residual strength, and fire resistance rating of concrete at different levels of HDPE and fly ash percent substitution. A quartic model was formed for f_c' while cubic models were formed for the RRS and FRR. All models were validated for the assumptions of response surface methodology, thus, this study has contributed to local research on sustainable materials [19-36].

5. ACKNOWLEDGMENTS

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