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Investigation on the Influence of Coal Ash Replacement and Seawater Mixing and Curing on the Strength of Concrete

Paul Bryan P. BIDOL[1] , Ronaldo S. GALLARDO[2] , Irene Olivia M. UBAY-ANONGPHOUTH[3]

***Abstract*— Fly ash and bottom ash are two of the most common waste materials produced in the Philippines. Due to the potential environmental problems posed by these by-products, proper waste disposal is a major concern. As a solution in the local setting, coal ashes were incorporated in concrete mixing as partial replacement for cement and fine aggregates. Furthermore, in efforts to produce sustainable concrete, seawater was introduced as a replacement for freshwater. This research focused on investigating the various influences of replacement materials with respect to the compressive strength development of concrete. The experiment tested the compressive strength of the modified mix containing alternative materials, with varying fly ash ratio of 0, 10, 20, 30, and 40%, respectively, and a constant 20% bottom ash replacement. The results show that fly ash replacement, curing days, and the interaction between the medium and the fly ash content significantly affect compressive strength development, and that the optimum fly ash replacement for maximizing compressive strength is 30-35%.**

Keywords— ***fly ash, bottom ash, seawater, compressive strength, optimization***

I. Introduction

The construction industry in the Philippines is steadily growing, with a forecast of 7.5% growth per annum between 2013 and 2016 (Business Monitor International, 2012). This development indicates a high demand in major construction materials, primarily concrete and steel. The use of these two materials is of vital importance in the erection of structures because of their properties: concrete is particularly strong in withstanding compressive stresses, and is highly fire-resistant; steel reinforcements are added in concrete to complement its low tensile strength, since steel is very strong in tension. The combination of concrete and steel makes for an ideal construction material capable of resisting natural and induced forces present in the environment.

However, the Philippines is not without limitations. Cement, a crucial constituent in concrete responsible for binding the rest of its components, had a series of price fluctuations in the past. The fluctuations can be attributed to the steady increase of cement demand throughout the years, and to the varying price of fuel and coal worldwide (Manila Bulletin, 2011). There had also been instances where shortage in cement occurred in the country, such as the domestic shortages in the early 1950s, 1970s, and in 2010 (Cement Manufacturers Association of the Philippines, 2012; CEMNET, 2010), thus creating a need for materials which may be substituted to cement in concrete production.

Another problem encountered in the Philippines is the water usage in construction industry. While agriculture consumes 88% of the overall potable water supply in the Philippines, the construction sector still use 4% of the available water, which is still substantial (Senate Economic Planning Office, 2011). Despite an abundance in water sources, the geographical distribution of these bodies of water is not uniform, thus making freshwater inaccessible to some areas (Senate Economic Policy Office, 2004). The United Nations have also reported that Philippines is one of the countries which may experience water scarcity by the year 2025, if current trend in population increase continues (2011). Due to the archipelagic condition of the Philippines, the utilization of seawater may be more practical whenever it is applicable. A study showed that in an ordinary Portland cement (OPC) concrete mix, the samples cast and cured with ocean water slowly increase in compressive strength, but the values were lower compared to the sample mixed and cured in seawater (Emmanuel, Oladipo, & Ogunsanmi, 2012). The result is generally positive, since it lengthens the service life of the concrete by providing a steady development of strength. Seawater is also discovered to cause early strength gain in concrete (Mohammed, Hamada, & Yamaji, 2004).

As an active response in solving the aforementioned problems, several replacement materials were introduced and were substituted over the conventional materials. Fly ash and bottom ash were used as cement and fine aggregate substitutes, and seawater was used as a replacement medium for freshwater. Studying the effect of these substitute materials in the strength development may help in alleviating the problems in the construction sector, and may encourage a more widespread use of alternative materials.

II. Methodology

This study focused on determining the possible influences of replacement materials on the compressive strength of concrete. Three factors were considered, namely the type of medium (factor A), the amount of fly ash replacement (factor B), and the length of curing day (factor C). In order to monitor the development, a total of 250 cylindrical specimens were created, having a dimension of 100 x 200 cm. The specimens were divided into two major groups: the freshwater group and the seawater group. Each group was cured in a separate tank. They are further divided into five groups, each corresponding to particular fly ash replacement percentages of 0, 10, 20, 30

Paul Bryan P. BIDOL, Ronaldo S. GALLARDO, Irene Olivia M. UBAY-ANONGPHOUTH
De La Salle University – Manila, Republic of the Philippines

and 40%. All samples, except the 0% control mix, had a constant bottom ash replacement of 20%.

The compressive strength testing is spread throughout a 70-day period, having a total of five testing days starting on the 14th day after curing. The succeeding tests were then conducted at a 14-day interval until the 70th day is reached.

The mix design used in the experiment is in accordance with ACI 211.1, with a water-cement ratio of 0.45. The aggregates and the cement used were supplied by TRISTAR Ready Mix, Inc. in Makiling, Laguna and were tested using ASTM Standards C 127 and C 128. The fly ash and bottom ash used in the study were sourced from coal-fired power plants located in Iloilo City, Philippines. The final mix design is shown on Table I.

The compressive strength data were collected for two months, and were then analyzed using Design Expert 7.0. The program was used in the creation of interaction plots and in conducting optimization. Response Surface Methodology (RSM) – General Factorial Design was used in determining the optimum amount of fly ash replacement for both freshwater and seawater groups.

III. Summary of Results

The result of the experiment showed the different effects and interactions between the replacement materials. Initial statistical analyses show that the type of medium used does not significantly affect the long-term strength development of concrete. Although there are differences in strengths on the 28th day, the overall behavior of the data indicate that the compressive strengths of samples mixed and cured in either medium tend to attain comparable values after a long period of time.

TABLE I. MIX DESIGN OF THE STUDY

<table>
<tr><th>Replacement Ratio (%)</th><th>Water (kg/m³)</th><th>Cement (kg/m³)</th><th>FA (kg)</th><th>Sand (kg/m³)</th><th>BA (kg)</th><th>Gravel (kg/m³)</th></tr>
<tr><td>0</td><td rowspan="5">193.06</td><td>455.56</td><td>0</td><td>710.60</td><td>0</td><td rowspan="5">1009.48</td></tr>
<tr><td>10</td><td>410.00</td><td>45.56</td><td rowspan="4">568.50</td><td rowspan="4">142.10</td></tr>
<tr><td>20</td><td>364.45</td><td>91.11</td></tr>
<tr><td>30</td><td>318.89</td><td>136.67</td></tr>
<tr><td>40</td><td>273.34</td><td>182.22</td></tr>
</table>

The length of curing day of the samples, on the other hand, was significant in strength development. All specimens, regardless of the replacement ratio and the medium type used, experienced an increase in compressive strength as the curing day increased.

Similarly, the amount of fly ash replacement also proved to be significant in influencing the strength development on concrete. Throughout the testing period, the differences between samples per testing day remained significant: as the fly ash replacement percentage increased, the corresponding compressive strength decreased.

Duncan Multiple Range Tests (DMRT) for the freshwater group show that the 0% replacement group (control mix) tends to have the highest compressive strength value, followed by the 10% and 20% mixes which remained statistically similar in behavior for all testing days, while the 30% and 40% mixes had the least compressive strength value. This behavior remained consistent across all five testing days.

The DMRT results for the seawater group are similar to the freshwater group, however the difference lies in the final strength development. The control mix, together with the 10% and 20% mixes, had statistically similar behavior after a long period of time, which meant that the samples with fly ash replacement as much as 20% may attain values equal to the control mix. Despite being statistically different, the 30% and 40% mixes still attained compressive strength acceptable for practical construction application.

In comparing the strengths of the samples between the two groups, the seawater/freshwater ratio was calculated. This ratio indicates the percentage of strength attained by a seawater sample with respect to its freshwater counterpart.

The graphical representation in Fig. 1 shows a boundary value of 1.0, which denotes the condition that the strength of a seawater sample equals the strength of the freshwater sample for that given testing day. It can be seen from the graph that most of the samples in the experiments did not attain a value of 1.0, which is expected since the study utilized alternative materials.

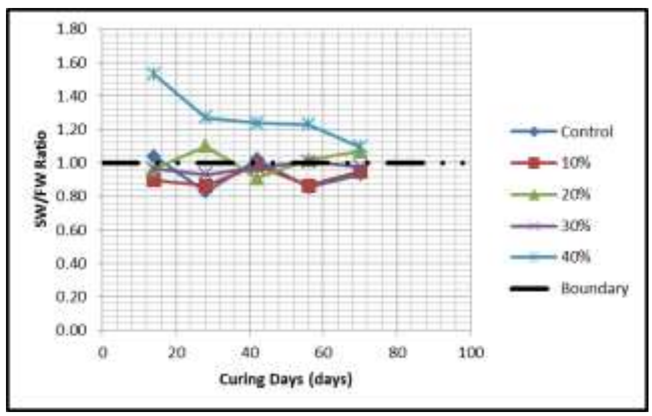

Figure 1. SW/FW Ratio for Varying Fly Ash Replacement

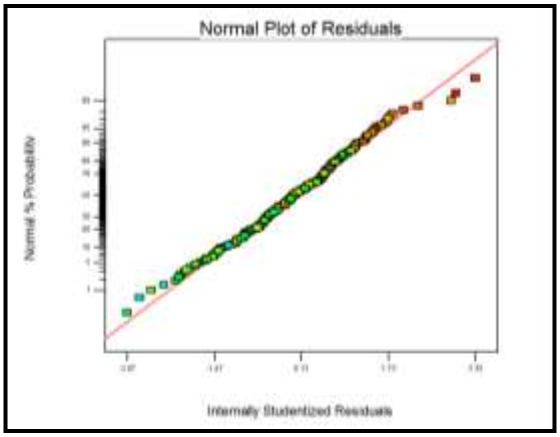

Figure 2. Normal Probability Plot of the Samples

However, it must be noted that the actual ratios are scattered near the boundary value, suggesting that mixes having seawater as the mixing and curing medium can still attain strengths comparable to mixes which used freshwater. The lowest ratio in the experiment is found to be 0.83 under the control mix, while the highest ratio is at 1.53 under the 40% mix.

A. *Interaction between factors*

The interaction between the factors was determined using Design Expert 7.0. The chosen method of RSM was General Factorial Design, since there are several levels considered for the fly ash replacement and curing days: there are a total of 50 combinations, stemming from 5 levels of FA replacement, 5 levels of curing days, and 2 levels of medium type. The study had 5 replicates for every combination to provide sufficient samples and also to protect the experiment from any unexpected external interference.

It has been confirmed through tests for normality that the probability distributions of the treatments are normal, and that the variances of these treatments are equal. The normal probability plot of the samples is shown on Fig. 2.

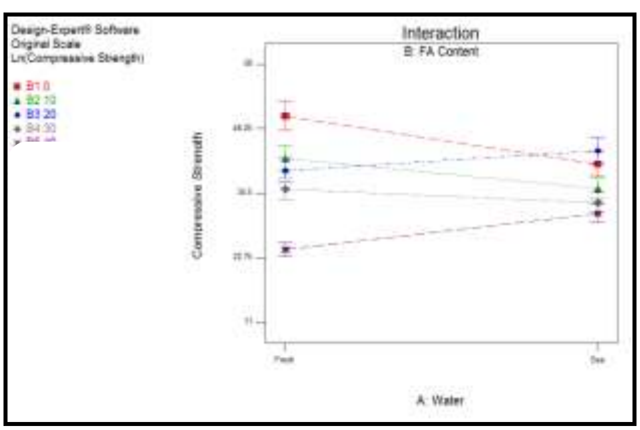

Figure 3. Interaction Plot for Medium Type and Fly Ash Content on the 28th Day

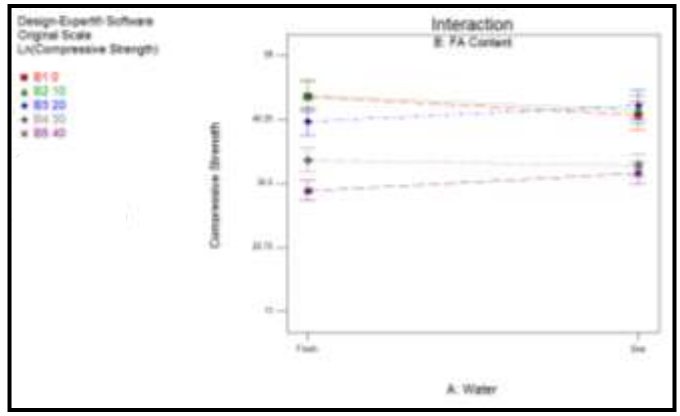

Figure 4. Interaction Plot for Medium Type and Fly Ash Content on the 70th Day

Based on the Analysis of Variance (ANOVA) F-Test, the significant factors which influence the compressive strength of concrete are the fly ash replacement percentage, the length of curing day, and the interaction between the medium and the fly ash replacement.

The interaction diagrams for the medium and fly ash replacement (interaction AxB) show the presence of an interaction between the two factors. As presented under Fig. 3, the interaction lines of the different mixing groups intersect one another. The trend of the lines show that as the percentage replacement of fly ash is increased, the more seawater becomes a suitable medium for the mix. This particular trend between the two factors remained almost the same until the 70th day of testing, which is shown in Fig. 4.

The possible interaction between the medium type and curing day (interaction AxC), and interaction between the fly ash replacement and curing day (interaction BxC) were deemed insignificant in the experiment. The interaction plots from the experiments show that factor AxC is present, but is deemed insignificant in the overall strength development because the interaction is dictated by the fly ash content. The occurrence of the interaction is constant at all levels of replacement, however weak or strong it is; however, the influence of the interaction is not caused by the two factors per se; it is further enhanced by the fly ash replacement, which causes a change in the influence of the interaction. The interaction could either impede or improve strength development, but not without the fly ash content intervening in the final outcome of the interaction itself. Interaction BxC, on the other hand, is insignificant because the main effects of the fly ash replacement and length of curing day have greater influence on strength.

B. *Optimization*

Since the objective of this study is the utilization of alternative materials, the data were further modeled using the same program. The response surfaces for the two groups were generated, as well as the corresponding contour graphs of the predicted strength values. Figs. 5 & 6 show the 3D graphical representation of the response surfaces for freshwater and

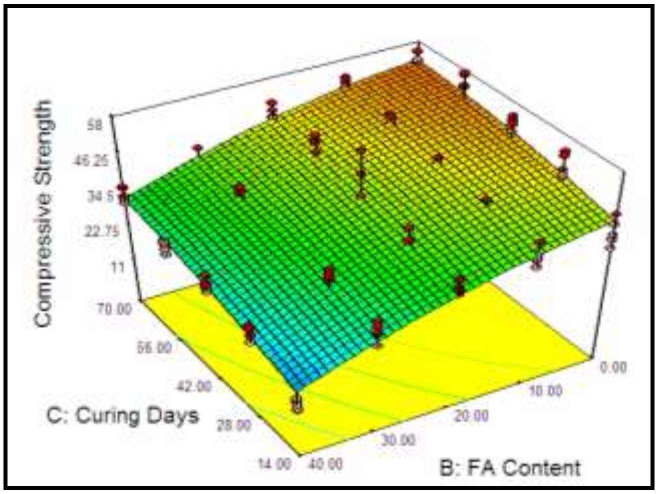

Figure 5. Response Surface Graph for Freshwater Group

seawater groups, respectively. The response surface is a quadratic model for both groups. The intensity of the colors on the graph represents the magnitude of the compressive strength values at a particular region: the hotter the color, the greater the strength values are. The projected contour graphs of the response surfaces are illustrated in Figs. 7 & 8.

It is evident from the 3D response surfaces that the highest point occurs when the length of curing day is maximized, and the fly ash replacement is at 0%. Thus, in order to determine the optimum mix design which considers the utilization of alternative materials, numerical optimization was conducted, wherein the researcher identified minimum conditions which would permit the use of replacement materials, and would eliminate points which yield strength values below the minimum strength limit of 17 MPa stipulated in ACI 318 – 11 standard.

The conditions imposed on the numerical optimization are as follows: FA content is to be maximized; and curing day must be within the range of 14 to 28 days, considering the practical curing time for a typical construction project. The response is intended to be maximized, with values ranging from 17.236 – 52.286 MPa.

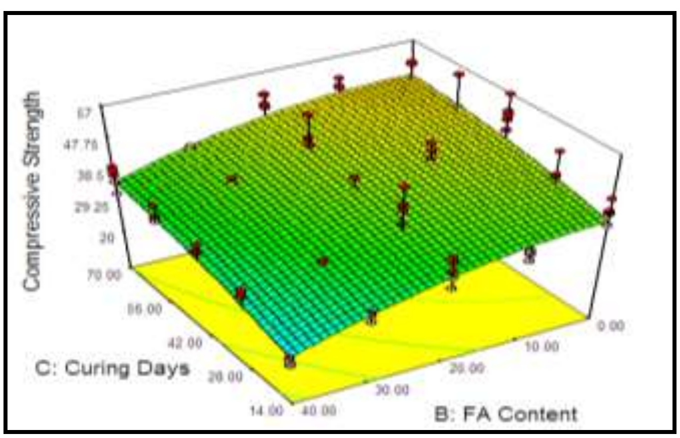

Figure 6. Response Surface Graph for Seawater Group

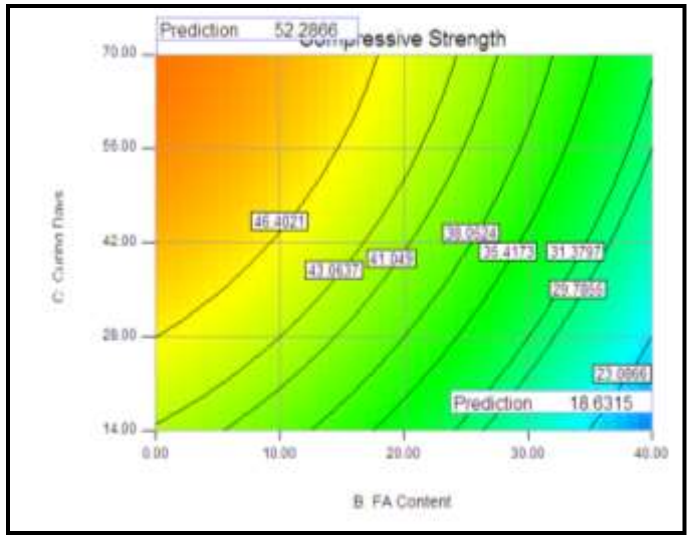

Figure 7. Projected Contour Graph of the Response Surface for Freshwater Group – Compressive Strength Values

The results of the analysis show that there are two possible optimized conditions for the freshwater group, as tabulated in Table II. The optimized conditions for the seawater group are presented in Table III. Optimization for both groups yielded the same strength at 30 MPa, with fly ash replacement values ranging from 30-35%, which is a sufficiently high percentage of replacement.

IV. Conclusions

Based on the results of the study, the following conclusions were formed:

- The medium used has no significant impact on long-term compressive strength development. Curing the samples for an extended period of time will contribute to an increase in compressive strength.

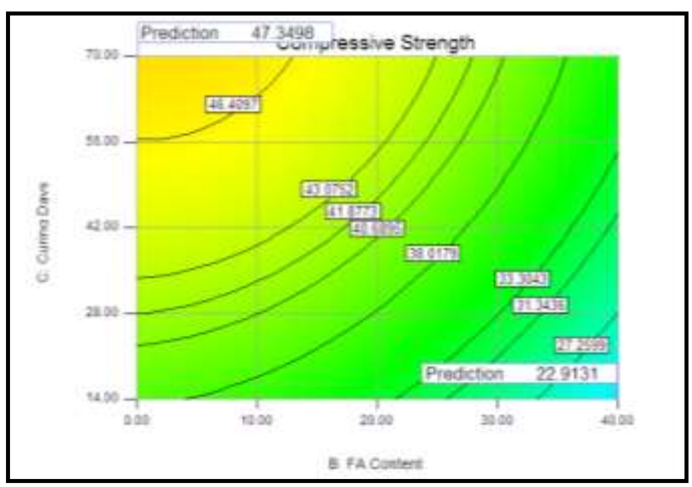

Figure 8. Projected Contour Graph of the Response Surface for Seawater Group – Compressive Strength Values

Figure 9. Optimized Conditions for Freshwater Group

Condition Number	Medium	FA Content	Curing Day	Compressive Strength
1	Freshwater	29.57	28.00	31.73
2	Freshwater	30.08	28.00	31.35

Figure 10. Optimized conditions for Seawater Group

Condition Number	Medium	FA Content	Curing Day	Compressive Strength
1	Sea	33.68	28.00	31.28
2	Sea	33.46	28.00	31.41
3	Sea	34.22	28.00	30.96

- Any fly ash replacement percentage permits steady development of compressive strength over time. However, an increase in fly ash replacement will decrease the potential of having higher development of compressive strength.
- The fly ash content, length of curing day, and the interaction between the medium and the fly ash content have a significant impact on the long-term compressive strength development of concrete.
- Seawater can be a viable curing and mixing medium, as demonstrated by its interaction with bottom ash and fly ash.
- Numerical optimization shows that the maximum fly ash replacement which could yield acceptable compressive strength values using freshwater as a medium is approximately 30%. It can produce a high compressive strength value of 30 MPa in 28 days. Similarly, the seawater group yields optimum compressive strength value of 30 MPa, but has a more flexible range of maximum fly ash replacement at 30-35%.

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About the Authors:

Paul Bryan P. Bidol is currently taking up Bachelor of Science and Master of Science in Civil Engineering at De La Salle University – Manila with specialization in Construction Technology and Management Engineering. He is a scholar under the Engineering Research and Development for Technology (ERDT).

Engr. Ronaldo S. Gallardo is an assistant professor in Civil Engineering at De La Salle University – Manila. He is also the current Associate Vice President for Facilities Management of the said university.

Engr. Irene Olivia M. Ubay-Anongphouth is an assistant professor in Civil Engineering at De La Salle University – Manila. She has consistently presented studies in various international conferences.