Optimization of the compressive strength of hair fiber reinforced concrete using central composite design

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Abstract. In society today, improper waste disposal brings about numerous problems. One of the most common residual wastes found in the municipal solid waste is human hair. This waste, which is evidently continuing to accumulate in disposal streams poses a threat if not disposed properly. Several studies have been done in the search for possibilities of incorporating hair to construction materials. In this study, the compressive strength of Hair Fiber Reinforced Concrete (HFRC) was studied aiming to find the combination that would yield the optimum compressive strength. A parametric study on the effect of amount of hair (1%, 2% and 3%) as well as length of hair strand (0.5-inch, 1 inch and 1.5 inch) on the compressive strength of HFRC was done. The results of the parametric study were used to find the optimum compressive strength. Utilizing the Central Composite Design (CCD) of Response Surface Methodology (RSM), a mathematical model was produced relating the parameters and the combination of parameters that would yield the maximum compressive strength. Based on the results, the mathematical model obtained a Coefficient of Regression of 0.9807 showing that the probability plot of the residuals fits the regression line. As generated by the mathematical model, a combination of 3.2% amount of hair by volume of concrete and a hair strand length of 0.752 inch will yield an optimum compressive strength of 38.15 MPa.

1. Introduction
One of the most widely used construction materials in the construction industry is concrete due to its high compressive strength, long service life and low cost [1]. However, concrete has low crack resistance and has limited tensile strength. The use of concrete ranges from its utilization in the construction of buildings to its versatility in highway construction particularly in the construction of roadways [2]. Moreover, the development of infrastructures (residential, commercial and industrial) depends on the performance of concrete [3]. Researchers have devoted their time in finding materials which can be added to concrete in order to improve its qualities. Due to the advances of concrete technology, fiber reinforcement was introduced. The reliability of Fiber reinforced concrete has already been established and is widely implemented in various range of applications in the industry. It has also been observed in previous studies that fiber reinforced concrete has a better performance as compared to normal concrete [4].

One of society’s major problems at present time is improper waste disposal. Often, inappropriate disposal of refuse (i.e. indiscriminate disposal of litter to streets) leads to clogging of drainages which is one of the culprits of street flooding. In all the residual wastes that are causing problems, human hair is one of the most overlooked. A common constituent found in municipal waste streams in most parts...
of the world is human hair [5]. Hair is characterized by its high tensile strength, thermal insulation and elastic recovery [6]. Studies have been done in efforts of managing our waste by means of incorporating fibers as composite in concrete [7]. Some of these studies are about the physical and mechanical properties of human hair [8-9]. There are also studies about the characterization of human hair and its applications but using it as reinforcement in concrete has not been adequately explored.

Response surface methodology (RSM) is a collection of mathematical and statistical techniques for empirical model building. By careful design of experiments, the objective is to optimize a response (output variable) which is influenced by several independent variables (input variables). RSM was developed to model experimental responses and then migrated into the modeling of numerical experiments [10]. The application of RSM to design optimization is aimed at reducing the cost of expensive analysis methods (e.g. finite element method or CFD analysis) and their associated numerical noise. The response can be represented graphically, either in the three-dimensional space or as contour plots that help visualize the shape of the response surface.

Central Composite Design (CCD) is a five-level factorial design that is used in the calibration of the quadratic response model [11]. The design model is utilized when generating a model that would yield the relationship between different variable inputs and the optimum condition of the output of the experiment. This study aimed to generate the relationship between input variables such as the amount of hair fiber (1%, 3% and 5%) by volume and hair strand length (0.5 in, 1 in and 1.5 in) using Central Composite Design of Response Surface Methodology (RSM) and determine the optimum compressive strength of Hair Fiber Reinforced Concrete (HFRC).

2. Materials
The supply of hair used in the preparation of concrete cylinders was collected from hairdresser shops, parlors, and salons along the city of Manila. The hair samples were washed and air-dried before including it in the design mix. Ordinary Portland Cement of a local company, fine and coarse aggregates was used for preparing the concrete samples. The materials used in this research were no less than the materials used in actual practice. The samples consist of cement, coarse and fine aggregates and collected hair.

The design mix is the process of determining the amount of cement, fine aggregate, coarse aggregate as well as the water/cement ratio and the target strength to be attained by the samples. The Class B concrete mix of 1:2.5:5 (cement: sand: aggregate) by volume with a water cement ratio of 0.55 was the basis for the proportions of the concrete. Hair fiber was incorporated to the concrete mix and was distributed well in order to prevent agglomeration as shown in Figure 1.

![Figure 1. Hair fiber incorporated in concrete.](image)

3. Experimental Methodology

3.1 Methodology on Parametric Samples

The concentration hair samples were varied as 1%, 3% and 5% per volume while the length of hair fibers was maintained and cut by 1-inch length for the initial samples, followed by 1.50-inch and 0.5-inch. The mix was poured into the molds in three layers as per the requirement of ASTM C-39 where each layer was compacted by 25 blows from the tamping rod. The sample was then lifted and dropped freely so that the air voids would be removed from the samples. The concrete samples were removed from the mold after 24 hours and were placed in a curing tank as shown in Figure 2 for curing periods.
of 7, 14, 21 and 28 days. The normal concrete samples were prepared in the same manner but without the incorporation of the hair fiber. ASTM C-39 was used in testing the compressive strength of the concrete cylinders.

Figure 2. The concrete specimens placed in the curing tank

3.2 Optimization using Central Composite Design

After the parametric study, the process of optimization was carried out. For this process, the Response Surface Methodology (RSM) Central Composite Design (CCD) which is a powerful tool in observing the interaction between the different parameters was utilized. RSM consist of a group of mathematical and statistical techniques for fitting linear response surface models in addition to a description of methods for the determination of optimum operating conditions [12]. Through this, a combination of parameters i.e. amounts of hair by volume and length of hair strand that would yield the highest compressive strength was produced (See Table 1). As suggested by the software, ten runs of dissimilar combinations of the different parameters were generated based on the numerical limits of the parameters presented. The software based the suggested values on the lower limit and higher limit of the parameters. The number of runs corresponded to the number of samples needed for the optimization process. After preparation and curing of these samples at different curing times (7, 14, 21 and 28 days). They were tested again to see the required compressive strength for optimization.

| Table 1. Suggested combination of parameters for optimization |
|-------------------------------------------------------------|
| **Runs** | **Amount of Hair (% by volume)** | **Hair Strand Length (in)** |
| 1        | 1                             | 1.50                        |
| 2        | 3                             | 1.7071                      |
| 3        | 1                             | 0.50                        |
| 4        | 3                             | 1                           |
| 5        | 0.1716                        | 1                           |
| 6        | 5.8284                        | 1                           |
| 7        | 3                             | 0.2929                      |
| 8        | 5                             | 1.50                        |
| 9        | 0.50                          |
| 10       | 3                             | 1                           |

An additional function of RSM aside from generating the optimum condition for a certain factor, also predicts the equation of the model as a multiple regression analysis. Equation (1) is the multiple regression observation.

\[
f(CS) = \beta_0 + \beta_1 A + \beta_2 B \tag{Equation 1}
\]
where $\beta_0$, $\beta_1$, and $\beta_2$ are the regression coefficients, while the factors of amount of hair by percentage of weight and hair strand length is denoted by A and B. A geometric illustration of the Central Composite Design is shown in Figure 3.

Figure 3. Geometric illustration of CCD

4. Results and Discussion

4.1 Parametric Study of HFRC

The compressive strength of the hair fiber reinforced concrete samples with varying amount of hair as obtained from the test results are shown in Figure 4. The highest compressive strength recorded at 38.10 MPa was obtained by the sample containing 3% hair by volume of concrete composite at its 28th day of curing as compared to 29.25 MPa of the sample without hair fiber. The addition of hair fiber led to a 30.26% increase in compressive strength compared to normal concrete.

Figure 4. Compressive strength of HFRC with varying amount of fiber.

Meanwhile, the results of the compressive strength test of concrete samples with varying lengths of fiber reinforcement is shown in Figure 5.

Figure 5. Compressive strength of HFRC with varying length of fiber.
Figure 5. Compressive strength of HFRC with varying hair strand lengths.

Based on testing, results show that the highest compressive strength was recorded at 34.07 MPa during the 28th day of curing with the sample containing 1in hair strand length. Comparing this to the control sample or normal concrete, which was recorded at 31.04 MPa, there is a 9.75% increase in the compressive strength with the addition of hair fiber in the samples.

Furthermore, for both cases of amount of hair fiber and hair strand length in the samples, it can be observed that the compressive strength of the cylinders starts to decrease after reaching a certain peak at the 21st day of curing. The further increase in concentration of fiber greater than 3% possibly led to excessive fibers which may also increase the void spaces in the concrete that reduces the compaction of the mix thereby decreasing the compressive strength.

4.2 Optimization by Response Surface Methodology Central Composite Design

Ten runs were generated by the CCD corresponding to the samples that needed to be produced and tested. After undergoing the compressive strength as per ASTM C-39, the results of the ten samples are shown in Table 2.

| Table 2. Compressive strength of samples generated by CCD |
|----------------------------------------------------------|
| Runs | Amount of Hair (% by volume) | Hair Strand Length (in) | Compressive Strength (MPa) |
|------|------------------------------|-------------------------|---------------------------|
| 1    | 1                            | 1.50                    | 30.18                     |
| 2    | 3                            | 1.7071                  | 33.79                     |
| 3    | 1                            | 0.50                    | 29.02                     |
| 4    | 3                            | 1                       | 39.25                     |
| 5    | 0.1716                       | 1                       | 24.36                     |
| 6    | 5.8284                       | 1                       | 28.99                     |
| 7    | 3                            | 0.2929                  | 31.38                     |
| 8    | 5                            | 1.50                    | 31.67                     |
| 9    | 5                            | 0.50                    | 28.70                     |
| 10   | 3                            | 1                       | 39.25                     |

By applying multiple regression analysis to the experimental data, the following mathematical model was found to represent the relationship between the responses indicated with the help of Sigma XL then obtained the generated model equation below:
RSM Regression Model: Compressive Strength = (39.25) + (0.964787789) * A: Amount of Hair (% by volume) + (0.941644994) * B: Hair Strand Length + (0.454894) * AB + (-6.2207545) * AA + (-3.2684865) * BB

Aside from the regression model, an estimate of parameters by Central Composite Design for Compressive Strength is shown on Table 3. As shown in the table, the p value of the parameter AB exceeds 0.05 (>0.05); thus, the significant effect on parameters on output response.

Table 3. Estimate of Different Statistical Parameters

| Term                              | SE Coefficient | T     | P      |
|-----------------------------------|----------------|-------|--------|
| Constant                          | 39.25          | 0.69095734 | 56.805 | 0.0000 |
| A: Amount of Hair (% by volume)    | 0.964787789    | 0.34547867 | 2.793  | 0.0492 |
| B: Hair Strand Length              | 0.941644994    | 0.34547867 | 2.726  | 0.0527 |
| AB                                | 0.454894       | 0.48858062 | 0.931052 | 0.4045 |
| AA                                | -6.2207545     | 0.45702532 | -13.611 | 0.0002 |
| BB                                | -3.2684865     | 0.45702532 | -7.152  | 0.0020 |

Shown in Table 4 is the Standard Error (SE) Coefficient and Variance Inflation Factor (VIF). The SE Coefficients range from 0.3 to 0.7 indicating that the predictions were precise and significant. SE Coefficient represents the average distance that the observed values fall from the regression line. Conveniently, it tells how wrong the regression model is on average using the units of the response variable. Smaller values are better because it indicates that the observations are closer to the fitted line. With the values of the SE Coefficient shown, the mathematical model is said to be adequate in this parameter.

Table 4. Statistical Performance Criteria

| Term                              | SE Coefficient | VIF |
|-----------------------------------|----------------|-----|
| Constant                          | 0.690957345    |     |
| A: Amount of Hair (% by volume)    | 0.345478672    | 1   |
| B: Hair strand Length              | 0.345478672    | 1   |
| AB                                | 0.488580624    | 1   |
| AA                                | 0.457025325    | 1.225 |
| BB                                | 0.457025325    | 1.225 |

Variance Inflation Factor (VIF) measure how much variance of the estimated regression coefficients are inflated as compared to when the predictor variables are not linearly related. It is used to describe the multicollinear property of the equation or the correlation between the predictors or input variables. Parallel to this, the variables being tested should not be highly correlated so as not to be subject to a domino effect of errors.

Based on the mathematical model, the coefficient of regression ($R^2$) is 0.9807 showing that the plot of residuals fits the regression line well. The results were used to produce a surface contour plot showing the interaction between the parameters and the compressive strength as shown in Figure 6 and Figure 7. The optimum compressive strength lies between 38 MPa to 40 MPa as shown in the figures.
From Figure 6, it can be seen that the parameters of amount of hair (% by volume) and the length of hair strand prove to be significant to the compressive strength because the contour plot yields an increasing trend in the compressive strength with the optimum output can be interpreted as the peak of the contour plot. The value of the concentration of hair which yields the maximum compressive strength is 3.2% and the corresponding length of hair strand is 0.752 inches and obtaining the optimum compressive strength at 38.15 MPa.

5. Conclusion

This paper aimed to evaluate the compressive strength of Hair Fiber Reinforced Concrete and compare it to normal concrete as a potential way of hair disposal and study the influence of concentration of hair and hair strand length on the compressive strength of concrete. The results of the parametric study were used to get the interaction between the parameters to get the combination that would yield the optimum compressive strength using Response Surface Methodology Central Composite Design. From the results, the following conclusions are made:

- Due to the addition of hair fiber, there is an evident increase in the compressive strength of the concrete samples compared to normal (conventional) concrete.
With respect to the amount of hair added to the samples, the HFRC with 3% amount of hair by volume of concrete composite yielded the highest compressive strength at 38.10 MPa compared to other concentrations.

Based on hair strand length added to the samples, the HFRC with 1-inch hair strand obtained the highest compressive strength at 34.07 MPa compared to the other hair strand lengths.

As generated by the Central Composite Design, a combination of 3.2% amount of hair by volume of concrete and a hair strand length of 0.752 inch will produce an optimum compressive strength of 38.15 MPa.

The use of RSM to develop a regression model for the optimization of the compressive strength of concrete proves that it is a powerful tool to determine the relationship between independent variables. Also, the different statistical performance criteria were used to check the validity and adequacy of the model and it showed that the mathematical model was a good fit for the data. The results obtained from the study shows the feasibility of using hair fiber as a form of reinforcement in concrete. The findings also signify that hair fiber can be used in the production of an innovative and low-cost construction material while serving as a waste diversion for hair in order to address the waste disposal problem of the community.

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