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MODELLING THE EFFECTS OF GEOSYNTHETIC REINFORCEMENT FIBERS ON THE STRENGTH PROPERTIES OF HARDENED CONCRETE

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Abstract - In the need to enhance the resilience of concrete structures and overcome the limitations of traditional steel reinforcements, which are prone to corrosion, geosynthetic fibers are being increasingly adopted as a viable alternative for reinforcement during construction, thereby improving the structures' ability to withstand stresses and deformations. The study models the effects of geo-synthetic reinforcement fibers on the strength of hardened concrete. The aim is to determine the effects of integrating geo-synthetic fiber in concrete-mix proportion on the strength of concretes and develop a model that can predict these effects. The research method involved the design of concrete-mix proportion with even material constituents, batched by weight and mixed until an even mix concrete matrix was attained. The mixed wet concrete was divided into two portions. The first portion was used to produce 12 Normal concrete cube samples of dimensions 150mm*150mm*150mm while the second portion was remixed with the addition of 12.5kg of geo-synthetic fiber and 12 geo-synthetic reinforced concrete cube samples were produced. All the samples (24) were cured and tested at their different testing ages of 7, 14, 21, and 28 days respectively. Model equations were developed to predict the effects of geo-synthetic addition into the concrete mix on the compressive strength of the concrete samples at different ages. From the results obtained, the reinforcement of concrete with geo-synthetic fiber increases the compressive strength of concrete by about 25% and the Model equations developed can predict the strength values of normal and geo-synthetic reinforced concrete structures with a correlation [R] value of 0.9128 and R^2 value of 0.8331. The study recommends the application of geo-synthetic fiber in concrete-mix proportion as it increases the strength and the adoption of the model equations for predicting the strength of both kinds of concrete provided that other extraneous conditions (e.g. mix ratios, water/cement, curing techniques, and test conditions) are unchanged.

Keywords: geosynthetic reinforced concrete, normal concrete, model equation

1. Introduction

Geosynthetics, according to the ASTM 1994 definition, are flat objects made of polymeric substances. They are utilized in conjunction with soil, rock, earth, or other geotechnical materials as an essential component of a civil engineering project, structure, or system. There are many categories for these materials, including Geotextiles, Geo-grids, Geo-composites, Fibrillated Geo-fibers, and Geo-filaments. Geosynthetics provide several roles, including acting as a barrier, facilitating drainage, offering filtration and separation, avoiding surface erosion, and enhancing the structural integrity of structures. Indeed, the number of geo-synthetics accessible in 1970 was limited to about 5 to 6, but in the early 2000s, the market offered over 600 distinct geo-synthetic products (Holtz et al, 1997, Holtz et al, 2008).

Geosynthetics primarily serve the purposes of separating, filtering, draining, reinforcing, providing a barrier against fluids, protecting the environment, and controlling erosion. Geosynthetics are offered in many shapes and materials, each tailored to a somewhat distinct purpose. Geosynthetics function as soil reinforcement through the following mechanisms: (a) augmenting shear strength by resisting the interface between the soil and geo-synthetic; (b) providing anchorage or resistance to being pulled out when subjected to forces; (c) offering tensile membrane and lateral deformation restraint effects to support typical burden. These actions lead to a decrease in shear stress on the soil below, a reduction in permanent deformation, and an improvement in bearing capacity (Ahmed et al 2022, Bourdeau and Ashmawy, 2015; Espinoza and Bray, 1995; Shukla, 2015a; Shukla, 2015b). Shear stress weakens the foundation's ability to support weight, which in turn undermines the stability of the embankment (Jewell, 1996; Rowe et al., 1987). Introducing a geo-synthetic reinforcing layer between the fill and the soil reduces the shear stress exerted on the soil foundation. The primary purpose of these structures is to enhance the stability of soil in Mechanically Stabilized Earth (MSE) walls and Reinforced Earth (RE) walls. The inclusion of fiber together with a cement of Portland type, in controlling poorly grained soil materials is adopted to amend the adversarial properties of those finely-grain soil particles in other to optimize its mechanical properties (Consoli et al, 2017)

Nevertheless, geo-synthetics are widely used in concrete constructions nowadays. These materials are often used in different ratios to assess and enhance the engineering characteristics of concrete, hence increasing its strength in withstanding lateral loads. When added in the appropriate ratio, this component significantly enhances the strength and longevity of the concrete. As a result, the compressive strength of the concrete is higher than that of regular concrete, providing a notable improvement for concrete. ‘They are used to enhance drainage by establishing a "slender" surface for water to traverse’ Kercher (2010). However, ‘there is a potential for deterioration if the material is exposed to sunshine and some highly corrosive substances’ (Okunade, 2010).

Geotextiles improve the durability and longevity of road infrastructure by effectively handling heavy loads and minimizing rutting. They provide stability and segregation, effectively limiting the movement of foundation material during compaction or loading. When fixing up old asphalt roads, geotextile is a common liquid barrier to use. Here, asphalt tack cloth is applied to the pavement surface before the nonwoven geotextile is laid down. An impermeable membrane is formed when the geotextile material absorbs asphalt, reducing the amount of water that may penetrate pavement structures vertically. Geotextiles provide substantial benefits when used for filtering purposes in road construction (Meccai and Hasan, 2004, Christofori dou Eirini 2021).

1.1. Statement of Problem

The durability of a robust structure to endure the impacts of weathering, chemical attack, abrasion, and other types of degradation during its lifetime with little maintenance is as important as its capacity to resist external forces. Though concrete has numerous benefits in terms of its mechanical properties and economic viability in building, nonetheless, its brittle nature is a substantial encounter in seismic and other applications that need to show some flexibility behavior. Normal concrete structures often experience lateral stresses when exposed to a load. These stresses induced as a result of applied loads, lead to the creation of cracks due to horizontal pressures and differential settlements in localized areas. This study, therefore, proposes the use of Geo-synthetic reinforced concrete design as a qualitative approach to enhance the structural performance of concrete structures and reduce the occurrence of failures caused by lateral forces in building structures.

1.2. Aim and Objectives of study:

This work aims to develop a precise model that appropriately depicts the influence of incorporating geo-synthetics in concrete structures. To actualize this aim, the following objectives were carried out:

1. Identify and classify the geo-synthetics available in the country according to their functions.

2. Evaluate the engineering importance of geo-synthetics as a reinforcement in concrete structures.
3. Compare the shear strengths of geo-synthetic and non-geo-synthetic reinforced concrete.
4. Establish a mathematical model for the shear strength of geo-synthetic reinforced concrete.
5. Compare the results observed from the experiment and the developed model equation.

The increasing demand for durable and resilient concrete structures has necessitated the development of innovative solutions to mitigate deformation and corrosion challenges associated with traditional steel reinforcement rebar. To address this need, the incorporation of geosynthetic fibers as reinforcing elements has emerged as a viable alternative to steel reinforcements. This approach not only enhances the structures but also reduces the risk of failure caused by lateral forces, such as earthquakes and high winds. Furthermore, geosynthetic reinforcement concrete design offers a qualitative approach to improving the overall performance of concrete structures, including enhanced tensile strength, improved crack resistance, and reduced maintenance requirements. By adopting this innovative design approach, the construction industry can create more sustainable, resilient, and durable concrete structures that can withstand the test of time and environmental extremes.

2. Theory on Modeling Approach to Evaluate Strength and Durability Improvements

The incorporation of geosynthetic reinforcement fibers into concrete is a method used to enhance its mechanical properties, such as tensile strength, flexural strength, and durability. Geosynthetics, typically made from polymers like polypropylene or polyester, are embedded within the concrete matrix to provide reinforcement and crack resistance. The modeling of their effects involves analyzing how the fibers interact with the concrete under various loading conditions. Key aspects include:

1. **Fiber Distribution:** Uniform distribution of fibers improves load transfer and crack bridging capacity.
2. **Bond Strength:** The interaction between fibers and the cement matrix determines the efficiency of stress transfer.
3. **Mechanical Properties:** Models assess changes in compressive, tensile, and flexural strength, typically showing increased performance compared to unreinforced concrete.
4. **Durability Factors:** The fibers reduce shrinkage and enhance resistance to environmental factors, improving the concrete's lifespan.

Finite Element Modeling (FEM) and experimental validation are often employed to simulate and analyze these effects, providing insights into the optimized design and performance of fiber-reinforced concrete for construction applications.

3. The Research Methodology

The design methodology is based on the molding of concrete cube samples of a particular mix ratio for both geo-synthetic reinforced and non-geo-synthetic reinforced concrete, and then testing their respective Compressive strength having been cured for 28 days. Three steps will be taken to actualize the objectives of this research.

Step 1: Molding of 12 concrete cube samples each for geo-synthetic and non-geo-synthetic reinforced concrete making it a total of 24 samples.

Step 2: Curing and determination of the samples' Compressive strength after 7, 14, 21, and 28 days respectively.

Step 3: Modelling the Compressive strength of the Geo-synthetic reinforced concrete and that of Non-geo-synthetic reinforced concrete.

3.1.1. Sample Collection

The samples used for this study were produced from a concrete mixture with a Grade 20 ratio. This study focuses on the experimental evaluation of the impact of geo-synthetics, namely polymeric fiber, on the compressive strength of concrete. This has led to the production, hardening, and examination of 24 M20 concrete cube samples of dimensions 150 x 150 x 150 mm.

3.2. Experimental Procedure

Grade M20 characteristic strength of concrete for 28 days was used in the research. Their compressive strength parameter is 20N/mm^2. The M20 grade concrete is designed with a nominal ratio of cement**:** fine Aggregate (sand)**:** coarse aggregate (crushed granite stone) to water of around 1:1.5:3 while ensuring that the water-cement ratio falls within the range of 0.4 to 0.6. The composition consists of a blend of cement, fine aggregates (sand), and coarse aggregates. The component materials were measured by volume and mixed manually to achieve uniform color. Having achieved a uniform mix, the concrete was divided into two parts, with each part serving a distinct purpose. The first part of the wet concrete matrix was used to mold twelve (12) normal concrete cube samples without geo-synthetics. The second part of the concrete matrix was further mixed with the addition of about 12.5kg of geo-synthetic, (assumed to be half the volume of cement content in the concrete). Another 12 cube samples of geo-synthetic reinforced concrete were equally produced from this mix.

3.3 Curing method and determination of the samples' Compressive strength

All the 24 concrete cube samples produced from both the normal mix and the geo-synthetic reinforced mix, having been left to dry for 24 hours, were subjected to curing in a curing tank by complete immersion at a constant temperature of **27^{0}C**. Afterwards, the samples were subjected to a compression test using the Compression Testing Machine (CTM). This was done on the 7th, 14th, 21st, and 28th days respectively with three (3) samples each from geo-synthetic reinforced and non-geo-synthetic reinforced concrete crushed in each case.

3.4 Model Development

Mathematical models were developed to predict the average compressive strength of normal concrete and geo-synthetic reinforced concrete GRC blended at various ages of curing. The dependent variables for each model are the compressive strength of normal concrete and that of the GRC, the independent variable is the concrete curing age. The model equations are shown in Equations 3.1 and 3.2.

$$F_{NC} = \beta_1 e^{\beta_2 t} \quad (3.1)$$

$$F_{GRC} = \beta_1 e^{\beta_2 t} \quad (3.2)$$

F_{NC} is the average compressive strength of normal concrete (N/mm^2), F_{GRC} is the average compressive strength of the GRC (N/mm^2), t is the concrete curing age (Days), β_1 and β_2 are constants. Applying natural logarithm on both sides of equation 3.1 we obtain;

$$lnF_{NC} = ln\beta_1 + \beta_2 t \quad (3.3)$$

$lnF_{NC} \equiv Y, ln\beta_1 \equiv a, t \equiv x,$ and $\beta_2 \equiv b.$

$$\therefore \; Y = a + bx \quad (3.4)$$

Applying natural logarithm on both sides of equation 3.2 we obtain;

$$lnF_{GRC} = ln\beta_1 \, \beta_2 t \quad (3.5)$$

$lnF_{GRC} \equiv Y, ln\beta_1 \equiv a, t \equiv x,$ and $\beta_2 \equiv b.$

$$\therefore \; Y = a + bx \quad (3.6)$$

Through calibration, the constants a and b in Equations 3.4 and 3.6 can be determined using Equations 3.7 and 2.8 thus;

$$a = \frac{n\sum Y}{n} - b\frac{\sum x}{n} \quad (3.7)$$

$$b = \frac{n\sum Yx - \sum x \sum y}{n\sum x^2 - (\sum x)^2} \quad (3.8)$$

A mathematical model was further developed to predict the average compressive strength of the GRC, which is the dependent variable and the independent variable is the curing age (in days).

3.5 Statistical Assessment

The correctness and reliability of the created models were assessed using appropriate statistical criteria, namely the Coefficient of Determination (R2) and the Coefficient of Correlation (CORR).

4.0 Presentation of Results and Discussions

The observed results from the experiment on the determination of the geo-synthetic fiber reinforcement effects on the compressive strengths of hardened concrete cube samples, together with the strength values predicted by the formulated model equations are presented as follows:

The developed logarithmic Regression Model Equation that predicts the compressive strengths of Normal concrete at the various testing ages is as follows:

$$Y = 4.7236 + 4.8273\, Ln(X) + e \quad (4.1)$$

$$Compressive\ Strength = 4.7236 + 4.8273\, Ln(Days) + e \quad (4.2)$$

Where Y = $Compressive\ Strength,\ X = days\ of\ crushing, e = error\ terms$

The Model Equation 3.2 was used to calculate values of compressive strength predicted by the model as in Table 4.1.

Table 4.1: The experimental results of the compressive strengths observed from the Normal concrete and the developed Model equation predictions.

Days of Testing	Mean Compressive strength (N/mm^2) Normal concrete	Mean Predicted Compressive strength (N/mm^2) Model Equation I
7	14.90	14.353
14	16.35	16.751
21	18.33	19.149
28	22.23	21.547

The second developed Regression Model Equation that predicts the compressive strengths of Geo-Synthetic Reinforced concrete at the various testing ages is as follows:

$$Y = 5.9384 + 7.2294\, Ln(X) + e \quad (4.3)$$

$$Compressive\ Strength = 5.9384 + 7.2294\, Ln(days) + e \quad (4.4)$$

Where Y = $Compressive\ Strength,\ X = day\ of\ crushing, e = error\ terms$

The developed model equation 3.4 above was used to predict the compressive strength values of Geo-synthetic reinforced concrete as shown in Table 4.2.

Table 4.2 The experimental results of the compressive strengths observed from geo-synthetic fiber-reinforced concrete and developed Model equation predictions.

Days of Testing	Mean Compressive strength (N/mm^2) Geo-synthetic reinforced concrete	Mean Predicted Compressive strength (N/mm^2) Model Equation II
7	20.13	20.772
14	24. 69	24.0907
21	28.14	27.4093
28	30.04	30.728

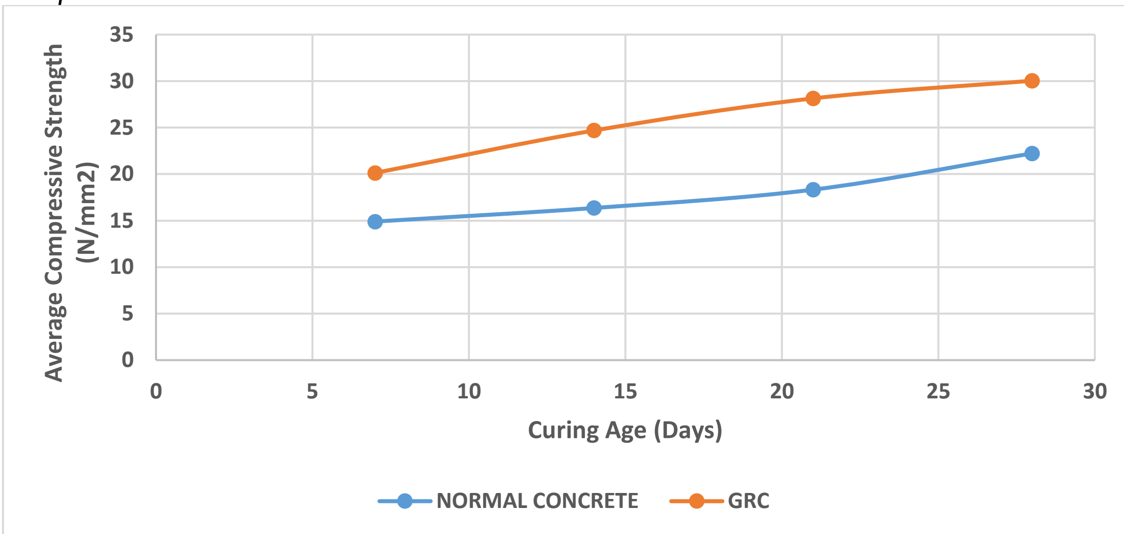

Figure 4.1: Average compressive strength against curing age for NC and GRC.

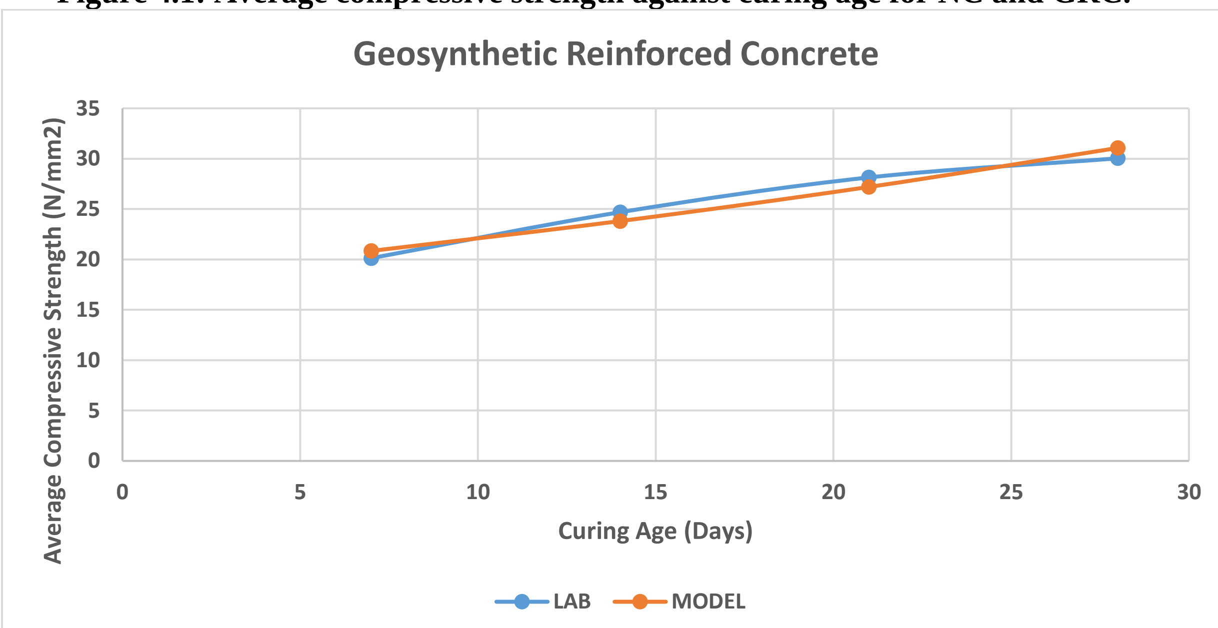

Figure 4.2: Model verification of the average compressive strength for GRC

The geo-synthetic reinforced concrete gave higher compressive strength values ($30.04\ N/mm^2$) than the normal concrete mix($22.23\ N/mm^2$) at the 28th day test for instance as could be deduced from Tables 4.1 and 4.2 and the pictorial view in Figure 4.1 above. However, when the results were tested for validation and hypothesis test for significance at 0.05 level through ANOVA Test. The result indicated that there was a significant difference between the mean compressive strength values of the two sets of concretes samples produced ($F_{cal}(29.02) > F_{crit}(4.3), p - value\ 2.075E - 05$). This implies that the addition of geo-synthetic reinforced fiber into the concrete design mix proportions, increases the strength of such concrete structures by about 25%. However, further research is needed as to determine the exact quantities of the reinforced fiber materials to be added into the mix ratio for optimum performances.

Table 4.1 above displayed the compressive strength results of concrete cube specimens from experimental observation for Normal concrete mix and those values predicted by the Model equation developed. The table depicts that the Model equation developed, predicted values that were very close to the observed experimental values while the slight difference could be considered as residual error as can be shown in Figure 4.2 above. The Model equation has a correlation [R] value of 0.9128, meaning that there is a very strong direct relationship between X (days of testing) and Y (compressive strength of concrete). The R-square (R^2) value is 0.8331 which means that 83.31% of the variability of Y (compressive strength) is explained by X (testing days) of the concrete samples. Therefore, the developed Model equation was able to predict the compressive strength values of the Normal concrete mix cubes for any testing age (in day), provided that other extraneous factors were kept constant and that the same concrete mix proportions, component materials, method of preparations and conditions of testing are uniform.

Table 4.2 exhibited the values from experimental results of compressive strength results of concrete cube samples produced with addition of Geo-synthetic reinforced fibers in concrete mix proportions and the values predicted by the developed Model equation. From the table, the Model Equation developed predicted values that were estimated to the experimental observed values, although the variance could be restrained as error terms. The Model equation correlates with [R] value of 0.9986, meaning that there is a very strong direct relationship between X (days of testing) and Y (compressive strength of concrete). The R-square (R^2) value is 0.9972 which means that 99.72% of the variability of Y (compressive strength) is explained by X (testing days) of the concrete samples. Therefore, the developed model was able to predict the compressive strength values of the Geo-synthetically reinforced fiber concrete cubes for any testing age (in a day), provided that other extraneous factors were reserved constant and that the same concrete mix proportions, component materials, quantities of geo-synthetic fiber material, method of preparations and conditions of testing are uniform.

The reliability of the two developed Model Equations that predicted compressive strength values of Normal concrete and Geosynthetic reinforced concrete were tested with a statistical method called ANOVA Test for the significant difference at 0.05 level of significance. The result indicated that there was no significant difference between the mean values of the compressive strengths predicted by the Mode equation and those observed from the experiments($F_{crit}(5.988) > F_{cal}(0.000388), p - \text{value } 0.9849$). This implies that the developed Model equation was reliable and able to predict the intended compressive strength values at any age as the concrete continues to develop in strength and should be adopted.

5.0 Conclusions and Recommendations

The following conclusions and recommendations were made based on the results revealed in this research

Conclusions

The geosynthetic reinforced concrete gave higher compressive strength values than the normal concrete mix at all the testing ages (in days). The result implies that the addition of geo-synthetic reinforced fiber into the concrete design mix proportions increases the strength of such concrete structures by about 25%. However, further research is needed to determine the exact quantities of the reinforced fiber materials to be added to the mix ratio for optimum performance.

The developed Model equations were able to predict the compressive strength values of the Normal concrete mix and geo-synthetic reinforced concrete cubes for any testing age (in a day), provided that other extraneous factors were kept constant and that the same concrete mix proportions, and component materials, method of preparations and conditions of testing are uniform.

The developed Model equations were reliable and able to predict the intended compressive strength values at any age as the concrete continues to develop in strength with time (in days). The result indicated that there was no significant difference between the mean values of the compressive strengths predicted by the Mode equation and those observed from the experiments

Recommendations

i. The research recommended the utilization of the two developed Model Equations for predicting the compressive strengths of both Normal concrete and geo-synthetic reinforced concrete structures.
ii. The integration of geo-synthetic reinforced fiber into concrete design mix proportions, as it increases the strength of such concrete structures.
iii. The research, however, recommend further research to determine the exact quantities of the reinforced fiber materials to be added into the mix ratio for optimum performances.

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