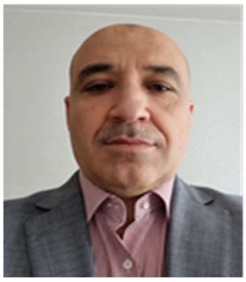
ISSN online 2545-2819
ISSN print 0800-6377

DOI: 10.2478/ncr-2024-0007

Received: April 23, 2024
Revision received: July 14, 2024
Accepted: July 23, 2024

Evaluating Concrete Strength Under Various Curing Conditions Using Artificial Neural Networks



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ABSTRACT
This study examines the impact of different curing methods on the compressive strength of concrete. It investigates techniques such as air curing, periodic water spraying, full water submersion, and polyethylene encasement. Artificial neural network models were employed to

evaluate the compressive strength under each curing condition. A model for calculating compressive strength that considers surrounding conditions was created using an artificial neural network. The current study's figures were generated using this model. The research thoroughly examined the impact of curing environments and concrete mix components on strength properties, taking into account factors such as temperature, the inclusion of additives such as fly ash and silica fume, adjustments in water-to-cement ratio, selection of aggregates, and the integration of various admixtures. One important discovery is that models that predict compressive strength based on 28-day water immersion do not accurately represent the actual strength because of the substantial impact of local curing conditions. Furthermore, concrete that was cured in polyethylene bags exhibited noticeable differences in moisture retention and temperature properties when compared to alternative methods. Understanding and evaluating curing conditions is crucial for accurate strength predictions. The study also found that compressive strength decreases with temperatures above 30°C and below 15°C.

Keywords: Concrete strength, artificial neural network models, parametric analysis, temperature effects.

1. INTRODUCTION

1.1 General overview

Concrete is widely recognized as the second most often used building material globally, surpassed only by water [1]. Its yearly use is estimated to be over 30 billion tons, a remarkable figure [1]. The primary reasons for its extensive popularity may mainly be its cost-effectiveness and convenient preparation methods. Despite being very prevalent, concrete is characterized by its intricate composition and several phases. Concrete formation entails complex chemical reactions, predominantly the hydration process, triggered by cement and water. Hydration, which plays a crucial role in the construction of concrete, results in the creation of novel crystalline structures, namely calcium silicate hydrates (C-S-H). The crystals play a vital role in aggregating particles, facilitating the progressive solidification of the concrete. The hydration process begins promptly upon the introduction of water and can continue for an extended period gradually enhancing the structural integrity of the concrete [1].

The utilization of concrete in engineered structures is essential due to its crucial functions in enhancing structural integrity and preventing the permeation of fluids. Nevertheless, the material's compressive strength is a critical technical metric for evaluating its resistance and general quality [2], making it a noteworthy predictor of its durability. It is crucial to recognize that many elements impact the compressive strength of concrete. The factors that influence the performance of concrete are numerous and varied. They encompass the characteristics of cement, the distribution of aggregate sizes, the ratios of different components in the mixture, and the incorporation of chemical and mineral admixtures [3].

The standard method for achieving maximum strength and good curing in concrete involves maintaining moisture for at least 7 days. The facilitation of concrete curing is commonly performed by techniques such as water immersion or continuous surface water spraying, which provide saturation conditions favorable for the concrete. Furthermore, within the construction sector, a wide range of curing aids are frequently utilized, including wet burlap, plastic sheets, polyethylene, and liquid curing chemicals. These tools are designed to meet the needs of efficient and timely construction and implementation. At times, curing chemicals are employed to safeguard the concrete surface and impede the process of water evaporation [4].

Despite the acknowledged significance of achieving a complete cure, numerous projects fail to meet this objective due to various obstacles. Several factors contribute to the challenges of managing water resources at construction sites. These factors encompass the restricted water supply, logistical complications associated with water transportation, the deterioration of water transport vehicles, and the strain imposed by faster building timetables. In such situations, the solid material is consistently exposed to the surrounding atmosphere and temperature conditions during its entire duration after being removed from the mold. The primary purpose of this study is to develop highly accurate numerical models that simulate various curing methods applied to concrete to estimate its actual compressive strength. Additionally, the study aims to gain a profound understanding of the effects of different curing techniques on the properties of concrete.

1.2 Research significance

Research plays a crucial role in advancing knowledge and understanding across all disciplines. It is fundamental in developing new theories, concepts, and methodologies. By systematically investigating and analyzing phenomena, research. Numerous scholarly investigations have been conducted to explore the impact of various curing methods on the characteristics of concrete. It is of utmost importance, however, to recognize a critical element of these research endeavors: they mainly occur inside the controlled settings of laboratory surroundings. The differentiation between laboratory settings and real building sites is of utmost importance due to the significant variations in practical situations that might be seen. The cautious extrapolation of laboratory findings to real-world settings is necessary due to insufficient facilities and variations in on-site conditions.

Acknowledging the prescribed 28-day period as a fundamental need for assessing the strength of concrete is crucial. Additionally, it is essential to recognize that the curing conditions to which concrete is subjected significantly impact its compressive strength. Given this context, there has been a collective endeavor within the scientific community to utilize sophisticated computer models grounded in ANN technology to forecast concrete's compressive strength under various curing circumstances. These models integrate a thorough examination of the fundamental elements that make up concrete mixes, taking into account their individual and combined effects on strength results.

This study holds scholarly significance as well as significant practical consequences. By facilitating more precise forecasts of concrete strength in different curing circumstances, these models have the potential to direct building practices, therefore enhancing quality control and optimizing material attributes. Furthermore, the application of (ANN models in this scenario highlights the increasing convergence of conventional civil engineering approaches with advanced computational techniques, signaling the emergence of a novel age characterized by data-centric construction and material science. Integrating empirical research with computer modeling can significantly transform the sector, providing detailed insights and improved predictability in concrete technology.

1.3 Literature review: enhanced detail and scientific integration

Curing is an essential construction procedure that enhances concrete's strength, durability, as well as overall quality, and several other building materials. This comprehensive literature analysis incorporates advanced scientific perspectives to analyze several external curing procedures, such as water curing, air curing, polyethylene sheet curing, and various water spray curing approaches. This study synthesizes the results of previous research to offer a full comprehension of their efficacy and ramifications for building methodologies.

Water Curing: Water curing is a building technique that requires continuous moisture maintenance in construction materials, often for at least 7 days. This technique is of paramount importance in mitigating moisture depletion in concrete, facilitating the process of hydration, and ultimately attaining the intended level of compressive strength. According to a substantial body of research [5], [6], prolonged water curing has a notable impact on enhancing the durability and fracture resistance of concrete. Techniques such as ponding, fogging, or wet covers play a crucial role in attaining these best outcomes since they guarantee a consistent and uninterrupted provision of moisture, which is vital for hydration.

Air Curing: Exposing concrete to the circumstances in the surrounding environment at the time of curing is what is meant by the term "air curing," which is synonymous with "natural curing." Research [6–8] into the effectiveness of air healing has revealed that its success is highly dependent on various meteorological factors. According to the research findings, although air curing may be advantageous in under-regulated or moderate settings, it may not produce ideal outcomes in harsh climates, particularly where quick evaporation or excessive temperatures are the norm. The studies highlight how important it is to optimize the exposure length and the ambient factors to improve the physicochemical reactions inside the concrete while it is air curing.

Polyethylene Sheet Curing: Polyethylene sheet curing is an effective approach for modern construction practices, involving enclosing freshly cast concrete within polyethylene sheets. This method is particularly beneficial for vertical elements, such as columns and walls, which are challenging to keep moist. This technique controls interior moisture levels and temperature conditions, essential to correctly setting and hardening concrete. The influence of this technique on the mechanical and long-lasting qualities of concrete has been investigated in research publications [9]–[11]. According to the findings, curing in polyethylene bags significantly enhances the effectiveness of the curing process, which is reflected in an improvement in compressive strength and an enhancement in durability. The mechanism may be explained by the impermeability of polyethylene, which plays the role of a moisture barrier and, as a result, encourages continuous hydration and the formation of microstructural features inside the concrete. These findings have been confirmed by further research [10–14], which shows that not only does this technique enhance the quality of the concrete, but it also contributes to the achievement of sustainability objectives by decreasing the amount of water used during the curing process.

An Increase in the Frequency of Water Spraying It has been shown that frequent water spraying is essential to treat damage in areas with severe circumstances, such as high temperatures and increasing evaporation rates. This technology guarantees that sufficient moisture is accessible for the ongoing hydration of cement, an essential component in producing concrete's necessary mechanical and durability qualities [5-7]. In addition, there are types of internal curing that were not included in the current study.

In summary, the curing process is a key factor in determining the mechanical and long-term qualities of concrete used in buildings. The complicated interactions between material qualities, project-specific needs, and environmental factors all affect the choice of curing procedure. For construction experts, it is essential to comprehend the scientific concepts that underpin various processes such as air curing, water curing, burlap curing, and curing chemicals. With this information at their disposal, companies may decide how best to use concrete in their projects in terms of quality and performance.

2. METHODOLOGY

Incorporating artificial neural networks (ANNs) into MATLAB constitutes a significant step forward in developing tangible technology, both in terms of theoretical investigations and actual implementations. Through this technology, researchers can construct complex models for predicting curing results, optimizing curing procedures, and eventually improving the quality and durability of concrete structures.

Concrete Curing and the Application of ANN Concrete curing is an essential procedure in the construction industry that substantially impacts the overall quality and the material's strength and longevity. ANN is utilized in this process. Recently, interest in using ANNs to improve concrete curing processes has seen a major uptick. ANNs, because of their capacity to absorb complicated information and learn from it, provide a novel approach to refining concrete curing procedures. A model for calculating compressive strength that considers surrounding conditions was created using an ANN. The figures shown in the current study were produced using this model.

The architecture and operation of Artificial neural networks (ANNs) are complex computer models that attempt to simulate the human brain's underlying neural architecture and computational processes. ANNs are made up of linked nodes, sometimes known as artificial neurons, and are organized into three layers: the input layer, the hidden layer, and the output layer. The basic goal of ANNs is to analyze data, learn from it, and make predictions or evaluations, similar to the cognitive tasks performed by the human brain [15]–[18]. In concrete technology,ANNs are used in conjunction with MATLAB to simulate the compressive strength behavior of concrete. This modeling considers various elements that influence the behavior of concrete, such as the components of the mix and the climatic circumstances under which it hardens.

ANNs and MATLAB in Civil Engineering: While strong, the employment of MATLAB and ANNs provides a steep learning curve for many civil engineers. The majority of civil engineers don't have deep experience in MATLAB programming [15]. To fill this need, the present research concentrates on the utilization of ANNs for calculating inter-layer weights and developing user-friendly models that are compatible with frequently used applications such as Excel. These models make quick calculations easier and are available to engineers without specific knowledge. They function with data input interfaces that accommodate the components of the concrete mix and the conditions of the environment, and they immediately compute the projected compressive strength by those particular conditions. Research [2, 15–17] backs up the effectiveness of this method.

Neural networks model and regulate the curing process by following the principles of data-driven learning, training, and generalization. This allows the neural networks to model and control the process. Training ANNs requires historical information that includes concrete compositions, ambient conditions, and curing procedures. During the training phase, the network parameters are adjusted to decrease the variation between the expected and actual results of the curing process. After training, the network can generalize its newly gained information to make accurate predictions regarding the impacts of new concrete compositions and curing circumstances. Neural networks provide robust capabilities for managing complex, high-dimensional data, adapting to new information, and discovering hidden patterns. However, these benefits come with challenges, such as the requirement for large datasets, difficulties in interpretability, and substantial computational resources. In summation, employing (ANNs in concrete technology, especially in curing processes, heralds a paradigmatic transformation in construction methodologies. This advanced approach significantly enhances the precision of predictive modeling and the efficiency of operational procedures within the building industry. Moreover, it fosters the development of construction practices that are not only more sustainable but also operationally efficient. The amalgamation of ANNs with accessible, user-friendly interfaces like Excel further facilitates the democratization of this sophisticated technology. This integration is instrumental in broadening the scope of its application across the construction sector, catalyzing a widespread adoption of more data-driven and intelligent building practices. This progressive shift is poised to redefine standards and expectations in the construction field, aligning with contemporary demands for sustainability and efficiency.

3. DATA GATHERING AND PREPARATION: ENHANCED SCIENTIFIC APPROACH

The component of this research including the collection of data and preparation required a thorough aggregation of 429 experimental concrete mixes taken from a variety of previous studies [7], [8], [11], [12], [14], [19]–[31]. These combinations represent various concrete compositions cured in multiple environments and provide a robust dataset for research purposes.These previous studies encompassed a variety of details about concrete mixtures, curing methods, and the cubic compressive strength at 28 days of each mixture, as shown in Table 1. While developing these prediction models, discrete subsets were taken from this dataset and used to construct the three different models. The first subset, which consisted of 246 combinations, was devoted to constructing a model that could predict concrete's strength when submerged in water or subjected to several cycles of water spraying. In a second selection of 118 combinations, developing a model to estimate the resistance of air-exposed concrete was the primary emphasis. The third group, which included 64 combinations, aimed to create a model to accurately forecast the compressive strength of concrete cured using a polyethylene sheet covering.

Validation of Models Each model went through a strenuous phase, using up to 90% of their individual data sets. The remaining ten percent of the data were used as a validation set, which were leveraged to determine the accuracy of the models by comparing their predictions to empirical findings in real-world scenarios. Notably, all three ANN models were tested with the experimental data, had exceptionally high levels of prediction accuracy, with success rates higher than 95%.

The following table provides an overview of the most critical factors and the variables that correspond to them, both of which played an essential role in the experimental examination of the compressive strength of concrete. The range of possible values for each parameter reflects the variety of investigated concrete mixes.

Table 1 – Parameters and Variables in Concrete Compressive Strength Analysis

Input	Description	Min	Max	Parametric study*	Unit
Cement	Cement content	104	544	380	kg/m^3
FA	Fly-ash content	0	275	0	kg/m^3
GPFS	Ground Granulated Blast Furnace Slag content	0	270	0	kg/m^3
SF	Silica fume content	0	110	0	kg/m^3
Water	Water content	105	270	180	Liters
Curing Time	Duration of concrete Curing	3.75	672	672	Hours
Coarse Agg.	Coarse Aggregate (Gravel)	537	1260	867	kg/m^3
Fine Agg	Fine Aggregate (Sand)	260	1948	793	kg/m^3
SPA	Superplasticizer amount	0	8.2	0	Liters
Air Content	Air content	0	6.4	0	%
Lap Temp	Laboratory ambient aemperature	10	45	20	ºC
Concrete Temp	Field ambient temperature	10	45	20	ºC
f_c	Compressive strength of concrete	15	101	-	MPa

*Note: The parametric study meticulously examines the isolated impact of each parameter on the compressive strength values, maintaining all other mix parameters constant.

This advanced analytical approach, encompassing a detailed and scientifically rigorous data gathering and preparation phase, provides a solid foundation for developing robust predictive models. These models are instrumental in enhancing the understanding of concrete behavior under varied curing conditions, significantly contributing to concrete technology and construction practices.

4. RESULTS AND DISCUSSION

It is noteworthy that the results presented in this chapter for the artificial neural network models under various curing conditions—such as water immersion, which including water spraying for different durations, covering concrete cubes with polyethylene bags, and air curing—were obtained using the same concrete mixes and tested for compressive strength at 28 days. The findings were discussed and compared with those from previous studies where applicable.

4.1 Temperatures and concrete curing dynamics

As is well known, the curing of concrete depends on several factors, the most important of which are the amount of available water and the ambient temperature. Each factor is influenced by the others. Generally, water immersion is the most effective curing method, followed by covering with polyethylene bags, and lastly, air curing. The ambient conditions significantly influence the curing process of concrete in its vicinity. This study component examined three unique curing scenarios: immersion in water tanks at temperatures ranging from 20 to 35°C, spraying concrete with water for limited periods of less than seven days, exposure to open air, and use of polyethylene sheets to cover the concrete during curing.

The reference temperature for concrete submerged in water was determined to be 20°C during the curing process. The research revealed a significant reduction in the compressive strength of the concrete as the water temperature for the curing process rose. Nevertheless, the correlation between these two variables was also impacted by the quantity of cement included in the mixture. According to the data presented in Figure 1, a, there is a positive correlation between the increase in cement content from 200 kg/m³ to 400 kg/m³ and the corresponding increase in compressive strength. A change in the behavior of concrete was detected after the cement content barrier was surpassed. The results are consistent with the experimental investigations cited in Reference [3], where a 365 kg/m³ cement concentration was employed.

The study determined that the ideal temperature for curing concrete in open air is 20 °C. As seen in Figure 1b, an augmentation in the cement content led to a concomitant enhancement in the strength of the concrete. This observation indicates a clear correlation between the quantity of cement in the mixture and the concrete's capacity to attain enhanced strength when subjected to curing in ambient air conditions.

Concrete curing under polyethylene membrane coverings exhibited distinct dynamics, as seen in Figure 1, c. In the given context, it was observed that the compressive strength of the concrete exhibited an upward trend when the cement content was raised to 350 kg/m³, ultimately reaching its peak strength under ambient temperature conditions. This observation suggests that each concrete mixture has a distinct threshold of cement content that must be met to get the maximum compressive strength, with the precise threshold being influenced by the curing technique. It may seem strange that the compressive strength decreases with an increase in the cementitious content of the concrete mix. Increasing the cement content without appropriately adjusting the water ratio may lead to higher density and dryness of the concrete, making the hydration process more difficult and resulting in lower strength. Additionally, covering the cubes with polyethylene bags may not be sufficient to ensure uniform moisture distribution, especially with higher cement content. This can cause uneven hydration between the surface and the interior of the cube, leading to reduced strength [32].

The findings presented in this study contribute substantially to comprehending the dynamics involved in the curing process of concrete, particularly when exposed to different climatic conditions. The research emphasizes the significant impact of temperature and cement content on the compressive strength of concrete. The results emphasize the need to meticulously choose curing conditions by the precise composition of the concrete mixture. By optimizing these characteristics, professionals can greatly improve the quality and longevity of concrete constructions. Moreover, the findings presented in this study provide significant implications for further investigation and practical implementations in the concrete technology domain, namely in advancing more effective and environmentally friendly curing methodologies.

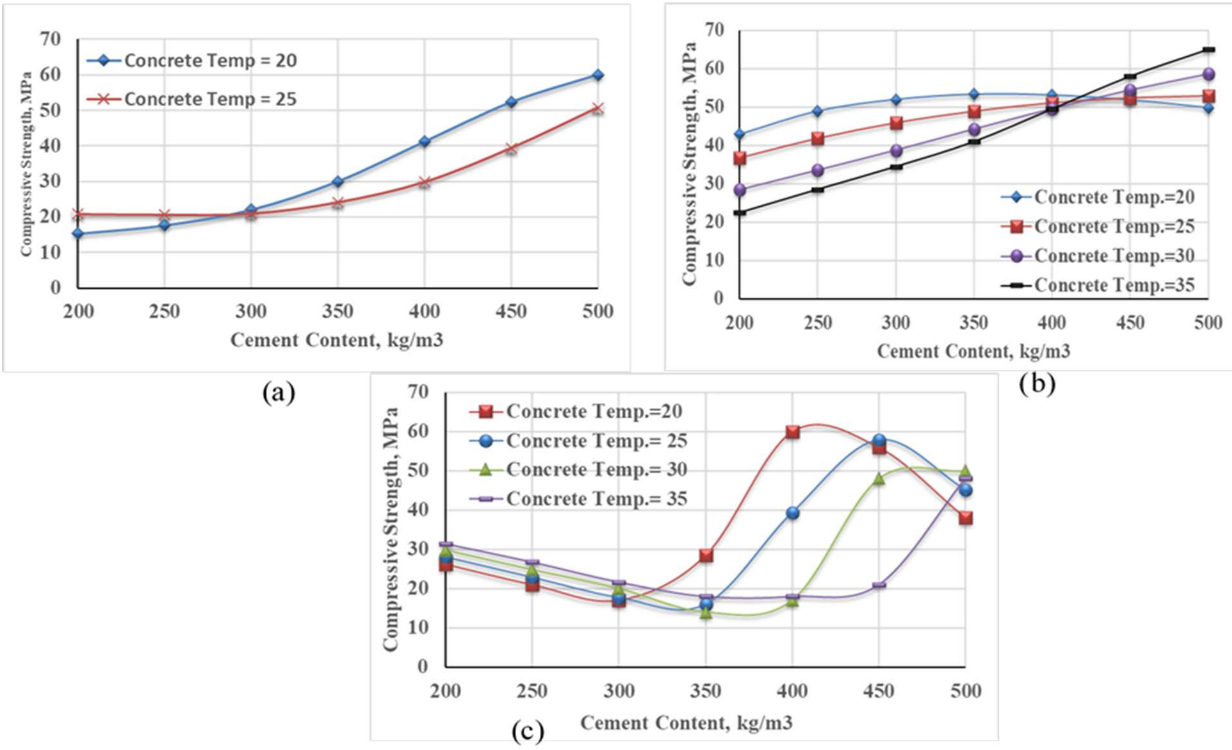

Figure 1 – Variations in Estimated Compressive Strength Relative to Temperature Under Different Curing Conditions (a) Water immersion Curing, (b) Ambient Air Curing, and (c) Nylon-Encased Curing

4.2 Fly-ash in concrete curing

Water-cured concrete

The Pozzolanic Reaction and its Impact on Microstructure: The incorporation of fly ash into concrete results in filling cavities with its tiny particles, leading to a more compact microstructure [32]. The principal chemical reaction entails the interaction between silica and alumina in fly ash and the calcium hydroxide liberated during cement hydration. This interaction results in the formation of supplementary calcium silicate hydrate (C-S-H) and calcium aluminate hydrate. The integration of fly ash at a rate of 13% has been demonstrated to increase compressive strength. Nevertheless, when the fly ash content increases to higher levels, such as 26%, the resulting reduction in calcium hydroxide content hampers the pozzolanic reaction. This phenomenon has been extensively discussed in the influential research conducted by Mehta and Monteiro on the microstructure of concrete [32].

The optimization of the fly ash and cement ratio. The optimal ratio of fly ash to cement composition is of utmost importance. The investigations conducted by researchers in references [23] and [33] propose a threshold at which adding more fly ash harms the desired outcome. The potential decrease in strength observed at greater levels of fly ash can be addressed by augmenting the cement content while ensuring the presence of essential ingredients required for the pozzolanic reaction.

Air-cured concrete
Influence of environmental surroundings on hydration kinetics The ambient circumstances impact the kinetics of cement hydration in concrete cured in air. The evaporation of moisture can hinder the process of hydration. However, fly ash, characterized by its small particle size and larger surface area, can positively impact water retention. The phenomenon above is accentuated in the comparative analyses conducted by [34-36].

In contrast to water curing, there are notable differences. The disparity in strength enhancement between air-cured and water-cured concrete, as seen in Figure 2. b, can be ascribed to variations in the hydration rate and the moisture presence. Several studies (19, 23, 30) support this discovery, demonstrating the unique behavior under various curing conditions.

Concrete curing with membrane covering
The curing environment exhibits distinct characteristics. The process of curing under a membrane creates a regulated environment for hydration. The membrane's moisture retention capacity improves the hydration process, impacting fly ash's reactivity. Utilizing a controlled environment can facilitate a more uniform and extended pozzolanic reaction, as evidenced by the research conducted.

The Interrelationship between Cement and Fly Ash: The efficacy of fly ash inside this particular setting is significantly contingent upon its ratio to the cement constituent. The literature supports the existence of a synergistic relationship between fly ash and cement in the specific curing conditions under investigation, as indicated by references [8], [19], [26], and [31]. This interaction has a discernible impact on the compressive strength of the concrete.

This comprehensive investigation offers a more profound understanding of the contribution of fly ash in concrete, encompassing the chemical and physical dimensions of its interaction with cement across various curing conditions. By including relevant research and ideas, this part not only adheres to academic norms but also thoroughly comprehends the characteristics and responses of materials under different curing conditions.

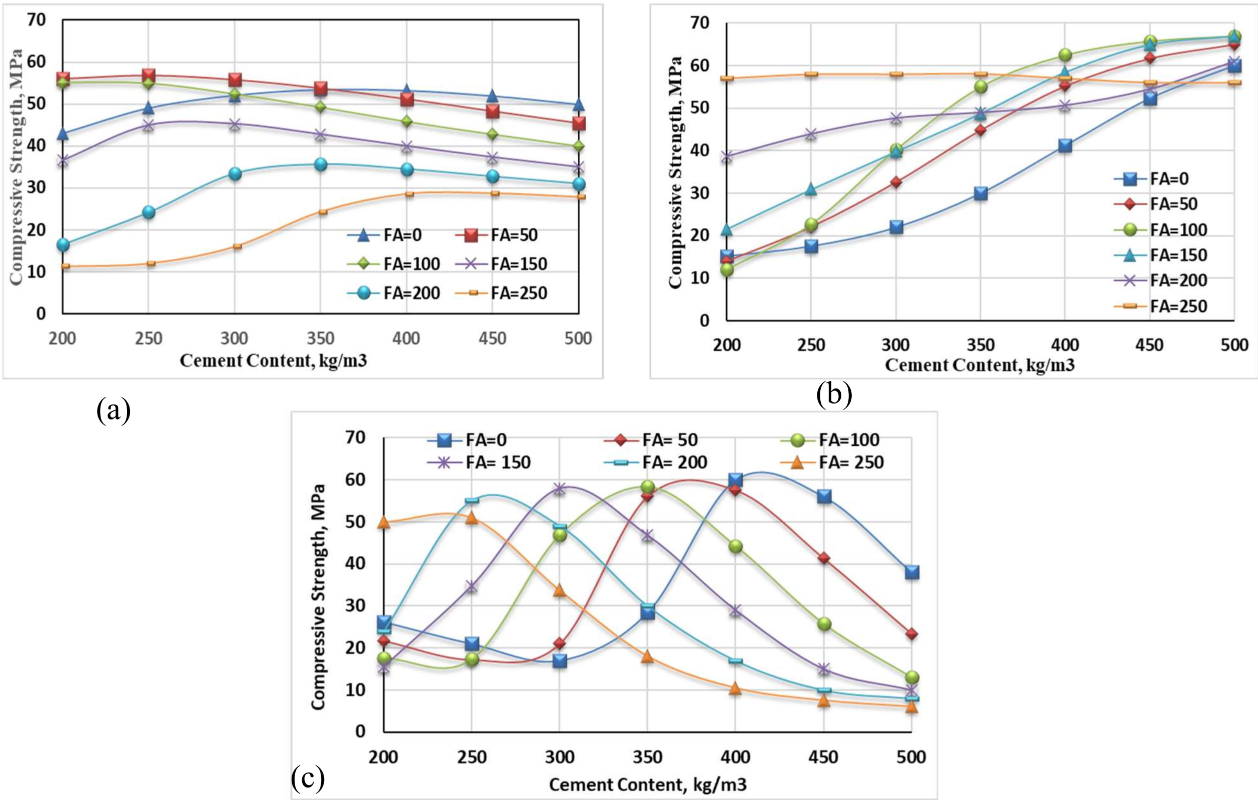

Figure 2 – Compression strength varies with fly-ash ratios with various maturing conditions, including (a) Water immersion Curing, (b) Ambient Air Curing, and (c) Nylon-Encased Curing.

4.3 Silica fume and its impact on concrete compressive strength

Strength, as depicted in Figure 3a. This phenomenon may be ascribed to the pozzolanic reaction of silica fume, leading to the generation of supplementary calcium silicate hydrate (C-S-H) gel. This gel plays a crucial role in enhancing the strength of concrete. Moreover, a good correlation exists between the augmentation of cement content and the enhancement of compressive strength. The results presented in this study are congruent with the experimental findings documented in References [11] and [23], indicating a continuous trend in the performance of concrete containing silica fume when subjected to water curing. When concrete is exposed to air curing conditions, silica fume can reduce compressive strength because it doesn't contain the necessary moisture for the pozzolanic reaction to develop fully. Water loss during air curing can also prevent cement hydration and the pozzolanic reaction between silica fume and calcium hydroxide, resulting in an incomplete response and decreased strength [33].

as depicted in Figure 3. b. The decrease in magnitude is especially evident when the amount of silica fume is less than 100 kg/m³, and the cement content is below 250 kg/m³ (40%). The probable cause for this phenomenon can be attributed to the inadequate moisture present during the air curing process, which hinders the complete pozzolanic reaction of silica fume. This reaction is essential for the development of strength. Nevertheless, it is worth noting that a rise in the cement concentration within the mixture leads to an enhancement in the strength of the concrete. The results presented in this study support the conclusions drawn in previous research studies cited in References [23] and [25]. These findings emphasize the significant role played by the proportion of silica fume and cement in influencing the compressive strength of air-cured concrete.

The present study highlights the intricate relationship between silica fume and cement concentration inside concrete. It elucidates how this interaction is affected by the conditions under which the concrete is cured. Silica fume is a proficient booster of compressive strength in water curing, mostly owing to the abundant presence of moisture that facilitates its pozzolanic activity. On the other hand, in the process of air curing, the reaction might be hindered due to insufficient moisture, resulting in a decrease in strength unless an increased amount of cement counterbalances this. The observations mentioned above have significant ramifications for the formulation of concrete mixtures, particularly when environmental factors pose limitations. Gaining insight into the behavior and characteristics of silica fume in concrete can contribute to the advancement of concrete technology by facilitating the creation of customized concrete mixes that are more durable and resilient, specifically designed to accommodate various curing circumstances.

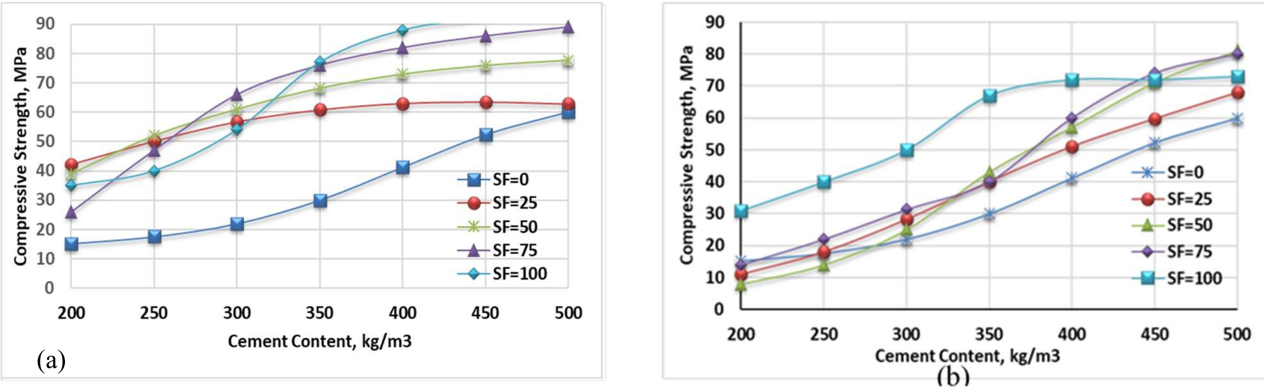

Figure 3 – Compression strength varies with silica fume ratios with various curing conditions, including water immersion Curing, (b) air Curing.

4.4 Water content and its impact on concrete compressive strength

The relationship between the water content and compressive strength of concrete is a multifaceted issue within the field of concrete technology, which is determined by the interaction of different components in the concrete mixture and the conditions under which it is cured.

The relationship between water content and compressive strength in concrete mixes often has a negative correlation, as more water content tends to have a detrimental impact on compressive strength. The relationship depicted in Figure 4. exhibits nuances in specific combinations, notably those characterized by low water content. In certain instances, an augmentation in cement content results in an unexpected reduction in compressive strength. This observation highlights the significance of the water-to-cement (w/c) ratio as a key factor in improving the compressive strength of concrete, rather than focusing just on the individual amounts of water or cement. The results mentioned above are consistent with the empirical assessments outlined in citation [3] and [25], which highlight the significant influence of the water-to-cement ratio on the design of concrete mixes.

The impact of curing concrete in open air on compressive strength is seen in Figure 4. b, where it is evident that an increase in water content leads to a reduction in compressive strength. Nevertheless, an augmentation in the cement content in the mixture correlates with a progressive enhancement in strength. The disparity in behavior observed between water-cured concrete and concrete exposed to open-air conditions can be ascribed to the absence of external water sources. Water curing involves immersing concrete compositions in water, partially satisfying their hydration requirements and facilitating maturing and hardening. The absence of an external water source in open-air curing renders the internal water content more crucial.

The compressive strength properties of different concrete mixtures vary throughout various curing circumstances, as seen in Figure 4. c. This observation suggests that its precise composition strongly influences the concrete's reaction to the curing process. The water content and the presence of cement and admixtures significantly influence the ultimate compressive strength of concrete.

This work offers significant contributions to understanding the intricate role of water in concrete technology. This statement emphasizes the need to adjust the water content and water-to-cement ratio to achieve the appropriate strength properties, especially when faced with different curing circumstances. The ramifications of these findings are of great importance for the design of concrete mixtures, as they indicate the need for a customized strategy that considers the unique conditions under which the concrete will cure and the desired characteristics of the material. A thorough understanding of the intricate interplay of water content, cement content, and curing conditions is of utmost importance in progressing concrete technology and enhancing concrete buildings in terms of resilience and efficiency.

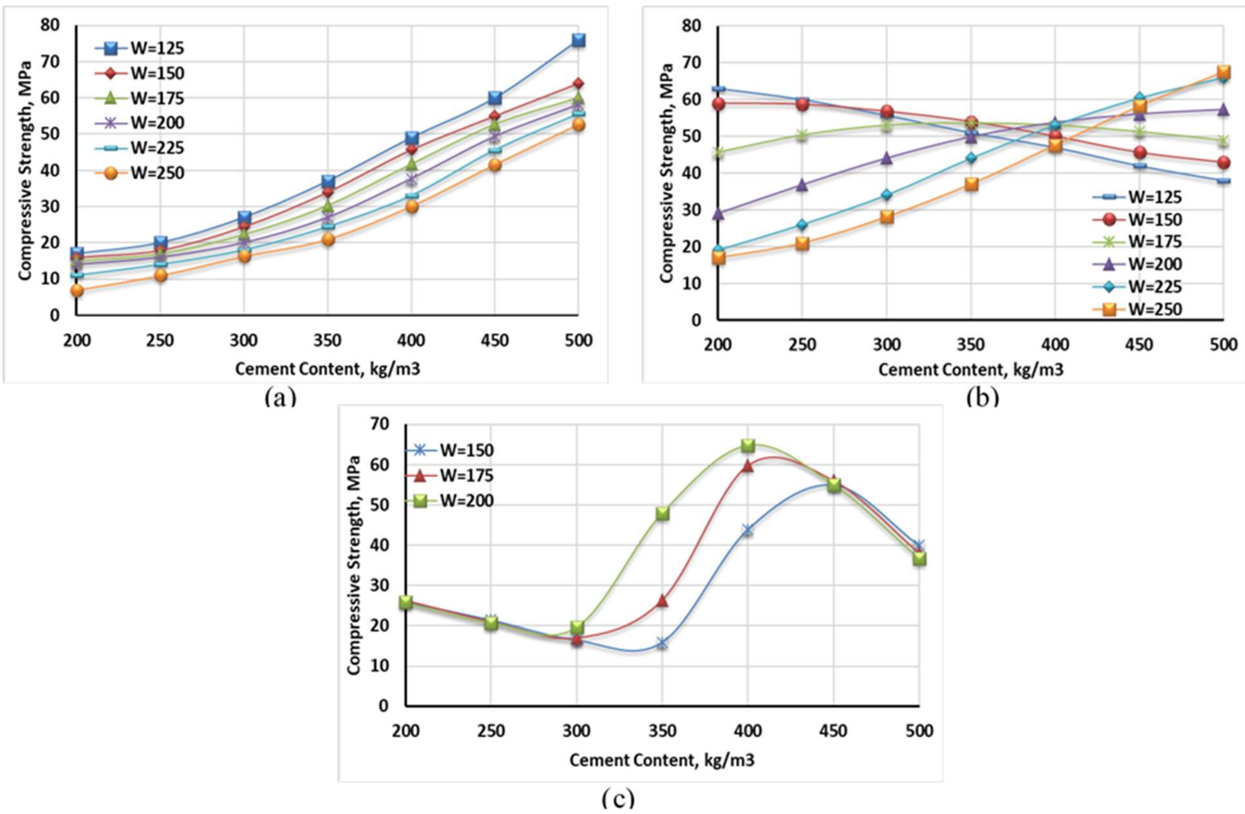

Figure 4 – Compression strength varies with water content with various maturing condition including (a) water maturity, (b) air maturity, and (c) nylon packing.

4.5 The impact of curing duration on compressive strength

The length of the curing process is a crucial aspect in the field of concrete technology, as it substantially impacts the progression of compressive strength in concrete structures.

The relationship between curing duration and compressive strength by established norms, as depicted in Figure 5, the research discovered that the compressive strength of concrete rises with extended periods of curing, especially when water spraying is utilized as a curing technique. This discovery is consistent with the recommendations outlined in American standards, which propose a minimum cure duration of seven days [19] and [34]. The proposal mentioned above is predicated on the premise that prolonged curing facilitates a heightened degree of hydration among cement particles, resulting in a more compact and robust microstructure inside the concrete.

The study observed a noteworthy correlation between cement content and curing efficiency. Additionally, it found that compressive strength declined beyond a certain threshold as cement quantity increased. The phenomena mentioned above, which have been supported by experimental investigations cited in references [19], [22], [31], [11], indicate an intricate interplay between the amount of cement used and the effectiveness of the curing process. The decline in strength observed at larger cement concentrations can be ascribed to many variables, such as inadequate water availability for the thorough hydration of all cement particles and the possibility of heightened shrinkage and crack formation. These phenomena have the potential to compromise the structural soundness of the concrete.

The findings of this research have significant theoretical implications and practical applications, as they enhance our overall comprehension of the dynamics involved in the process of concrete curing. Theoretically, it highlights the need to balance cement content and sufficient curing to achieve appropriate hydration and strength enhancement. The statement above underscores the importance of meticulously evaluating the combination ratios and curing protocols in concrete building endeavors to get the appropriate levels of strength and durability.

The above-mentioned findings underscore the significance of extended curing in promoting strength enhancement. However, it is crucial to exercise caution when considering the interplay between extended curing and cement content. The observation of diminished strength as cement content increases and curing times lengthen implies a threshold beyond which the positive impacts of cement content and curing duration are no longer advantageous. This observation holds special significance within the building sector, where the attainment of optimal concrete strength is of utmost importance. The statement mentioned above highlights the need to use a customized methodology to design concrete mixes and the curing process while considering the distinct demands of each building project. Comprehending these intricate connections is crucial for the progression of concrete technology and the assurance of constructing more tough and long-lasting structures.

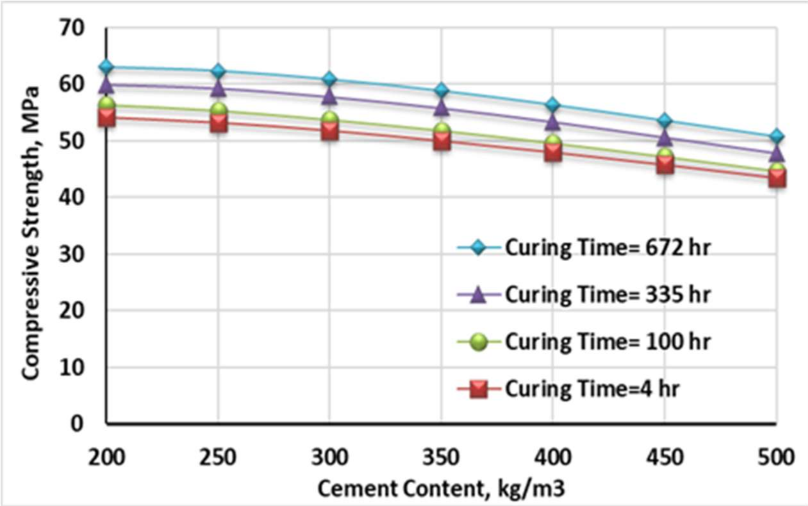

Figure 5 – *Compression strength varies with curing time.*

4.6 The influence of coarse aggregate on compressive strength

The impact of the amount of coarse aggregate on the compressive strength of concrete is a complicated phenomenon that is further influenced by various curing conditions. This interaction plays a crucial role in determining the overall structural integrity of concrete.

The study found that in water curing, an increase in the percentage of coarse aggregate generally reduces the compressive strength of concrete, as seen in Figure 6. a. The tendency mentioned above is notable when the quantity of coarse aggregate ranges from 550 to 650 kg/m³. Nevertheless, it is worth noting that within this specified range, a positive correlation exists between the increase in cement concentration and the corresponding rise in compressive strength. The decrease in strength resulting from an increase in coarse aggregate content can be linked to a decrease in the amount of cement paste, which is crucial for bonding and the development of strength. This observation aligns with the results obtained in previous research investigations [11], [25]. It underscores the importance of maintaining an appropriate equilibrium between aggregate and cement concentration to get the highest possible strength in concrete.

The study also observes that after the coarse aggregate content exceeds 750 kg/m³, additional increments in cement content do not yield substantial improvements in compressive strength. This phenomenon may be elucidated within the aggregate interlock and paste efficacy theoretical framework. Once a specific threshold is surpassed, an excessive amount of coarse aggregate has the potential to disturb the matrix, resulting in inadequate interlocking and diminished efficacy of the cement paste. Consequently, the advantageous impacts of extra cement are nullified.

Concrete compressive strength decreases with increased coarse aggregate content when the curing process is carried out beneath nylon covers, as depicted in Figure 6. b. However, the nature of this connection undergoes a transformation when the cement content is beyond the threshold of 350 kg/m³. In the given situation, when the proportion of cementitious material is raised, it starts to counterbalance the negative impacts caused by the increasing amount of aggregate. As a consequence, the compressive strength of each mixture is enhanced. This discovery, along with previous studies cited in References [7] and [22], highlights the compensatory function of cement content in mitigating the decrease in strength resulting from elevated amounts of aggregate.

The above observations contribute to a more sophisticated comprehension of the function of coarse aggregate within the concrete context. The optimization of aggregate content is crucial for achieving both structural stability and cost-effectiveness. It is necessary to consider the relationship between aggregate content, cement content, and curing conditions to ensure sufficient compressive strength. Maintaining this equilibrium is important in designing concrete mixes, especially when the utmost consideration is given to long-term durability and structural stability. The study's findings highlight the need to adopt a strategic methodology regarding concrete composition. This involves considering the interconnected impacts of all the mixture's components to get the intended mechanical qualities. Comprehending these interactions is crucial for the progression of concrete technology and the improvement of construction procedures.

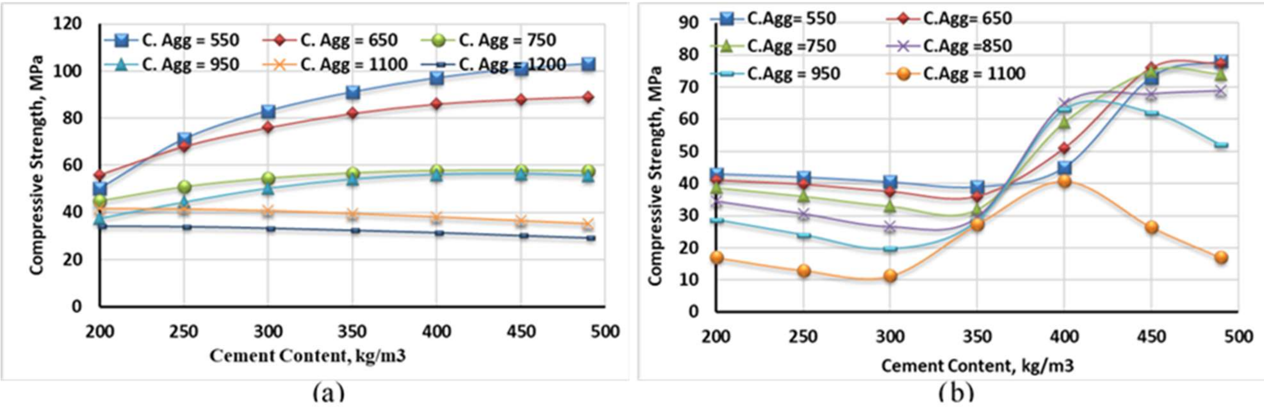

Figure 6 – Compression strength varies with coarse aggregate content with various maturing conditions, including (a) water maturity, (b) nylon packing.

4.7 Role of fine aggregate in concrete compressive strength

The research conducted in this study examines the impact of fine aggregate (namely sand) content on the compressive strength of concrete, considering different curing circumstances. The findings of this inquiry offer valuable insights that may be utilized to enhance the optimization of concrete mix design.

The compressive strength of water-cured concrete decreases as the amount of fine aggregate, namely sand, increases, as depicted in Figure 7a. The observed phenomenon, supported by research investigations [19], [31], can be ascribed to the dilution effect, wherein an excess of sand diminishes the proportionate amount of cementitious paste, vital for enhancing strength. Notably, a drop in compressive strength was noticed with an increase in cement concentration at lower sand percentages ranging from 300-800 kg/m³. The paradoxical nature of this conclusion might be attributed to the possibility of heightened water requirements, which in turn may lead to a deterioration of the concrete structure. On the other hand, when the sand content is larger (ranging from 950-1500 kg/m³), an augmentation in the amount of cement enhances the compressive strength. This implies that there was a more efficient distribution of cement paste and an improvement in the arrangement of particles.

In the context of air-cured mature concrete, it has been shown that including a higher proportion of fine aggregate, namely sand, leads to a corresponding increase in compressive strength. This relationship is visually depicted in Figure 7b. The observed phenomenon may be attributed to the enhanced arrangement of particles and decreased presence of empty spaces within the mixture, resulting in increased density and strength of the concrete. In addition, it has been shown that the compressive strength of concrete is improved when the cement concentration exceeds 300 kg/m³. This suggests that a larger cement content can offset the decreased efficiency of hydration that occurs during air-cured conditions.

When subjected to nylon coverings, the behavior of concrete demonstrates a discernible pattern, wherein each mixture displays elevated compressive strength at particular combinations of sand and cement content. For example, when the sand content is 300 kg/m³, the highest compressive strength is attained with a 300 kg/m³ cement content. According to Figure 7c, there is a shift in the optimal cement level for achieving optimum strength when the sand content increases to 500 kg/m³ and 800 kg/m³. Specifically, the ideal cement content changes to 350 kg/m³ and 400 kg/m³, respectively. This suggests that optimal compressive strength depends on the appropriate proportion of sand and cement, particularly when nylon coverings increase moisture retention . This can be explained by the fact that the study considered the effect of cement content independently, rather than the water/cement ratio. With the change in cement mixture contents and pozzolanic materials, and covering the specimens, the water content within the mix is relied upon exclusively without utilizing any external water content. Therefore, there is an optimal water-to-cement ratio that achieves the highest compressive strength. As a result, the graphs contained peaks where the water/cement ratio was optimal.

The findings above underscore the noteworthy influence of the quantity of fine aggregate on the strength of concrete and the intricate relationship between sand and cement under various curing conditions. The findings underscore the need to meticulously evaluate the sand composition in the design of concrete mixes, particularly concerning the amount of cement used and the conditions under which the concrete is cured. Comprehending these dynamics is crucial to generating concrete mixes that are economically efficient and demonstrate the requisite attributes of strength and durability. This comprehensive research offers useful insights for concrete scientists and practitioners in optimizing mix designs tailored to specific applications and curing circumstances.

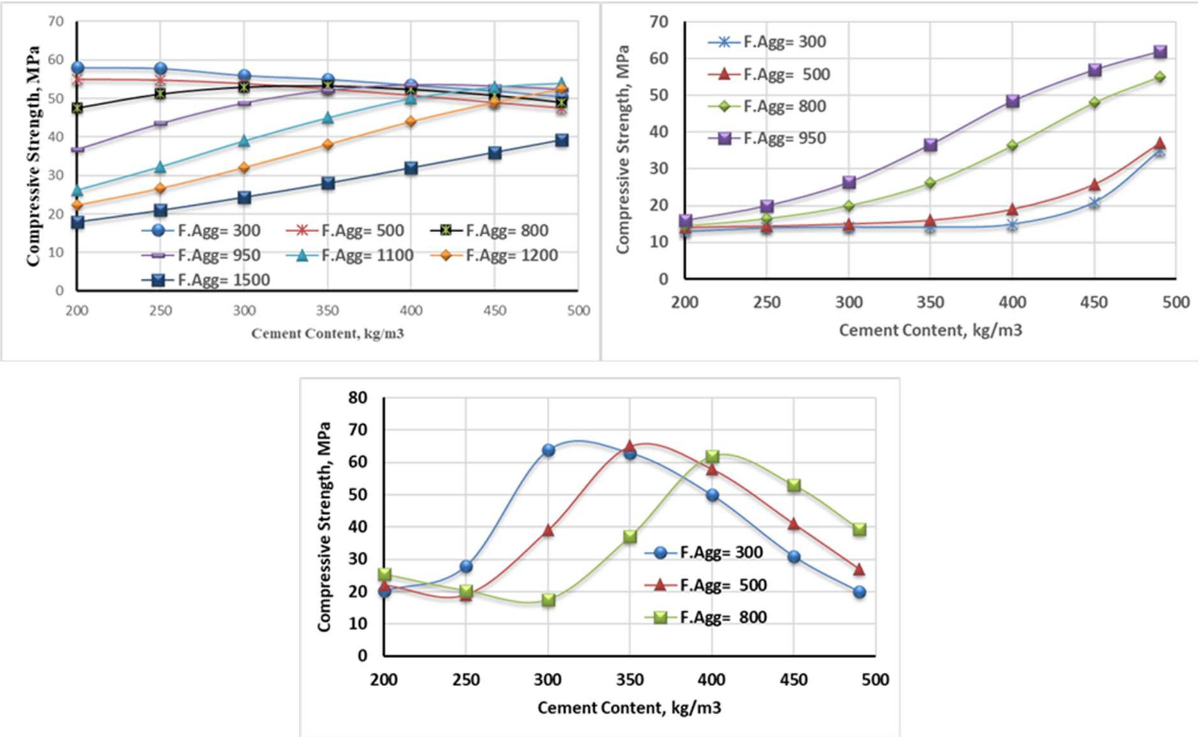

Figure 7 - Compression strength varies with fine aggregate content with various maturing conditions, including (a) water maturity, (b) air maturity, and (c) nylon packing.

4.8 Impact of superplasticizer (SPA) on compressive strength

The investigation conducted in this study examines the impact of superplasticizer (SPA) on the compressive strength of concrete under different situations. This research offers valuable insights into the rheology of concrete and its consequences for developing strength.[

The impact of varying cement contents on the compressive strength of concrete with the inclusion of Superplasticizer Admixture (SPA) is illustrated in Figure 8.a. It is seen that the incorporation of SPA leads to a notable improvement in compressive strength within the dosage range of 2 to 7 liters per cubic meter (L/m³). The observed enhancement may be ascribed to the capability of the Superplasticizer to decrease water requirements and enhance workability while maintaining the water-to-cement (w/c) ratio, hence leading to improvements in the microstructure and strength of the concrete. This relationship may be attributed to the enhanced dispersion of particles and the reduction in porosity resulting from the higher cement content. On the other hand, when larger superplasticizer (SPA) doses of 6-7 L/m³ are used, the material's compressive strength diminishes when the amount of cement exceeds 350 kg/m³. The observed phenomenon may be attributed to an excessive concentration of the concrete mixture, resulting in the separation and subsequent reduction in the strength of the concrete matrix.

Superplasticizer (SPA) behavior in air-cured mature concrete exhibits significant differences. The compressive strength is shown to decrease with an increase in the amount of SPA, as depicted in Figure 8.b. This phenomenon may arise as a result of excessive soluble polymer additives (SPA) in air-cured environments, which can result in heightened air entrainment and diminished inter-particle bonding, hence exerting a detrimental effect on the overall strength.

Nevertheless, it is worth noting that augmenting the cement content in such circumstances might improve the compressive strength, potentially offsetting the reduced hydration efficiency in locations where air curing is employed.

The influence of self-permeability agent (SPA) on concrete that has been cured beneath nylon coverings is shown to vary depending on the cement concentration, as depicted in Figure 8. c. When the cement concentration is less than 400 kg/m³, supplementary cementitious materials (SPAs) do not significantly impact the strength. Nevertheless, when the cement concentration surpasses 400 kg/m³, augmenting the dose of superplasticizer admixture (SPA) results in a decline in compressive strength. The loss in strength observed in the concrete may be attributed to an excessive amount of supplementary cementitious materials (SCMs), which can disrupt the optimal composition of the mixture. This disruption can dilute the cement paste and subsequently reduce the concrete's overall strength.

The findings mentioned above shed light on the intricate nature of surface-active agents (SPAs) and their ability to alter the physical characteristics of concrete. The effectiveness of SPAs in enhancing workability and lowering water consumption is well-documented. However, it should be noted that their influence on compressive strength is contingent upon factors such as cement content and curing conditions. This highlights the need to adjust the dose of supplementary cementitious materials (SCMs), such as silica fume, in formulating concrete mixes, specifically emphasizing the prevailing climatic conditions and the intended mechanical characteristics. Comprehending the interplay of single-page applications (SPAs), cement content, and curing settings is of utmost importance in formulating concrete mixes with optimal workability and the desired strength and durability attributes. This comprehensive research offers useful insights for concrete technologists and practitioners in improving mix compositions for diverse applications and curing circumstances.

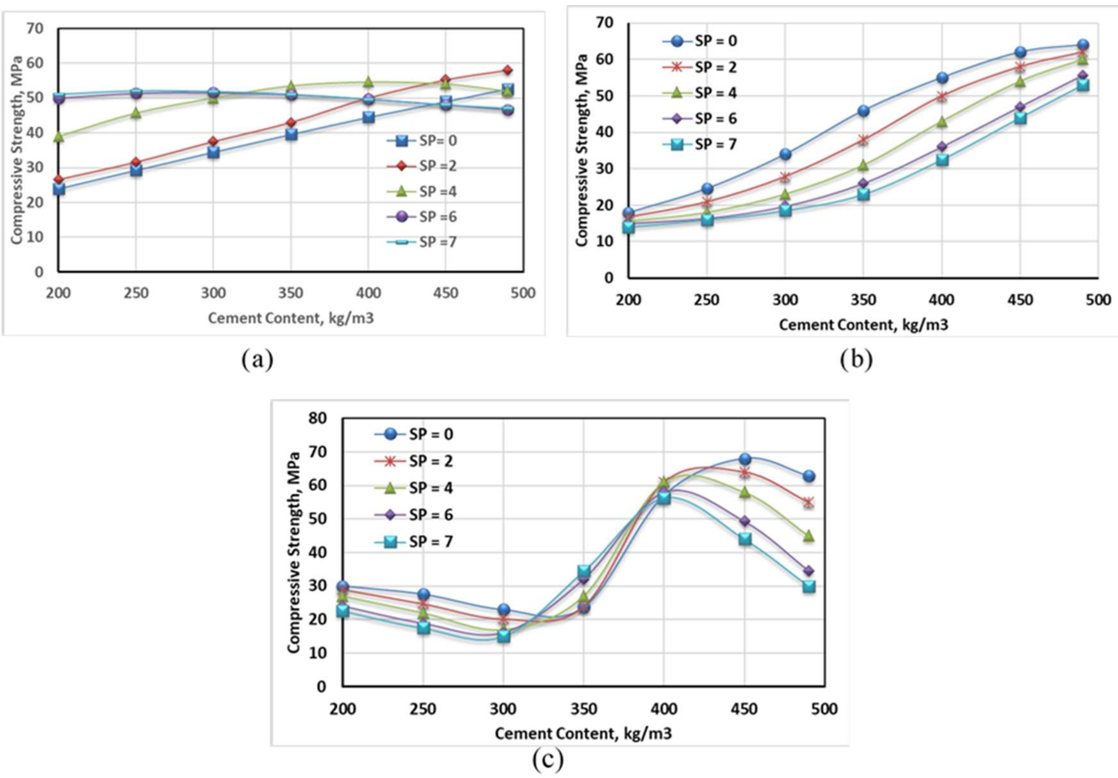

Figure 8 *– Compression strength varies with superplasticizer content with various maturing conditions, including (a) water maturity, (b) air maturity, and (c) nylon packing.*

5. CONCLUSIONS

The in-depth examination of the compressive strength of concrete under different curing settings has provided valuable findings, shedding light on the complex connections between curing techniques, constituent materials, and environmental variables.

Curing methods and compressive strength: The study provides evidence supporting the notion that water curing is the most productive approach for augmenting compressive strength. Subsequently, nylon-sealed curing ranks second in effectiveness, whereas air curing without any treatment exhibits the lowest efficacy. One significant discovery is the positive relationship between prolonged curing duration and enhanced compressive strength. Nevertheless, using this rule may not be uniformly valid owing to the distinct characteristics exhibited by individual concrete mixtures. The optimization of strength outcomes necessitates the use of tailored testing and assessment methodologies across diverse curing environments.

Temperature considerations: Maintaining a curing temperature in the vicinity of 20 °C is typically considered optimal. The research findings indicate a reduction in the material's compressive strength at age 28 days, when exposed to temperatures over 30 °C and below 15 °C. The observed phenomenon can be ascribed to the influence of temperature influences on the hydration processes and subsequent microstructural evolution occurring in the concrete.

The research findings suggest an ideal ratio of cementitious additions, such as fly ash, for each level of cement concentration. It is crucial to maintain a careful balance of these additives. Introducing excessive fly ash over the ideal threshold results in a decrease in compressive strength. This highlights the significance of establishing the optimal proportion of fly ash to the mixture's cement concentration and other constituents.

The utilization of silica fume has the potential to influence the compressive strength of a material positively. However, the extent of this impact depends on carefully managing the silica fume concentration, the amount of cement used, and the specific curing technique employed. Excessive utilization of silica fume in open-air curing may have counterproductive effects, reducing compressive strength. This may be attributed to the modification of hydration dynamics and the potential development of microstructural flaws.

The compressive strength of water-cured concrete typically decreases with increased water content. Nevertheless, this pattern is inverted when the cement concentration reaches around 400 kg/m³ since increasing amounts of cement begin to improve strength regardless of the water-to-cement ratios. During the process of curing under a nylon cover, it is seen that each mixture demonstrates a distinct optimal water content that results in the highest compressive strength. Generally, the strength of the mixture tends to increase as the water content is raised, up to a cement content of around 400 kg/m³.

Including a higher proportion of coarse aggregate in the mixture often leads to a decrease in compressive strength when the curing process occurs in a water tank. The phenomenon of nylon-covered curing exhibits comparable patterns but with a notable shift like the interaction when the cement amount is above 350 kg/m³. This suggests the presence of a multifaceted interrelationship between the aggregate and cement content.

The present paper comprehensively analyzes concrete technology, emphasizing the intricate interplay between aspects such as curing conditions, mix composition, environmental influences, and additive proportions. These factors together contribute to the determination of concrete's compressive strength. The results emphasize the need to adopt a nuanced and individualized approach when designing concrete mixes and formulating strategies for curing.

Comprehending these intricate relationships is vital to generating superior, durable concrete appropriate for various building purposes.

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