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Effect of Isothermal Curing on the Compressive Strength of High Early-Strength Concrete

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Abstract **-** Current utilization of high early-strength concrete has been a customary practice in majority of concrete pouring activities specifically for reinforced bulk/mass concrete foundation of structures nowadays. As a practical example, this type of concrete mix where satisfactorily employed for the concrete pouring of turbine-generator mat foundation for a coal-fired power plant somewhere in Batangas, Philippines. Technical preparations where undertaken to ensure and minimize the adverse effect on mass concrete such as coping up with the generation of cement heat of hydration and attendant volume change which may cause cracking. Sets of thermocouple device where directly installed to monitor and record the changes in temperature prior and after concrete pouring. It was found out from actual monitoring results that even after implementing respective adjustment on component temperature reduction of constituent concrete materials as well as the concrete mixture, the recorded temperature variation had exceeded usual threshold recommended by regular specifications and similar studies undertaken for this type of concrete. Compressive test results of cylinder samples corresponding to early-age (1, 3, 7 & 14 days) concrete strength showed notable increase in strength vis-à-vis elevated curing temperature; while ensuing 21, 28 & 56 day curing period had resulted in declining values as the isothermal temperature also normalize. As normal cured cylinder samples attain higher concrete strength as it aged, this trend were not identical and similar to the strength profile of tested isothermal cured cylinder samples, instead; a downward trending deviation in strength values were recorded. Thus this work gives us a good assessment that inherent chemical reaction and internal heat generation when not properly controlled, will adversely impact the strength of concrete samples at early and later age.

***Keywords*:** Isothermal curing; high early-strength concrete; high-strength concrete; reinforced mass concrete; mat foundation

1. Introduction

Recent advancement and innovation in concrete technology had paved way for robust application of admixtures that modifies the structural properties of concrete to suit and conform to actual project requirements and specifications. One type of specialty concrete products that is now widely available is the use of new polymer-based superplasticiser for high-strength concrete commonly classified as Type "G" admixture. This class of admixture is commonly applied as concrete additive especially for massive reinforced concrete structures such as bulk foundations where efficient workability and high slump pumpable concrete and a low water to cement ratio is utilized to achieve the desired high strength concrete. As per ACI 116R, mass concrete is defined as: "any volume of concrete with dimensions large enough to require that measures be taken to cope with the generation of heat and attendant volume change, to minimize cracking". Although numerous studies and guidelines were already undertaken to better understand the effect of restraint, volume change and reinforcement on cracking of mass concrete, the issue of concrete strength is relegated secondary to the expected volume changes due to thermal, autogenous and drying shrinkage. Specifically, for reinforced mass concrete structure wherein reinforcement is utilized in order to minimize and control the occurrence of thermally-induced cracks, the concept on the possible effect of temperature variation on the actual strength of reinforced concrete structure comes into consideration.

With most specifications of reinforced mass/bulk concrete structures such as foundations of structures referring only to the structural strength of concrete to measure its performance and durability, the results of in-place practice of getting field test specimens and measuring its relative compressive strength as the basis for evaluation and acceptance of the structure has been the usual practice. Although considered to be a representation of the poured in-place reinforced mass concrete, the curing process may not simulate the actual conditions that this sample may be exposed to; since actual curing process takes place in a controlled environment (where the sample is stored at a moist condition with free water maintained in their surfaces at all times at a temperature of 73±3°F (23±2°C) [4].

For instance, actual temperature monitoring for a poured mat foundation of a turbine-generator using high-early strength ready-mix concrete had shown an extremely high temperature readings exceeding 100°C (Fig. 1), which is way beyond the temperature limits covered by similar technical studies and related publications.

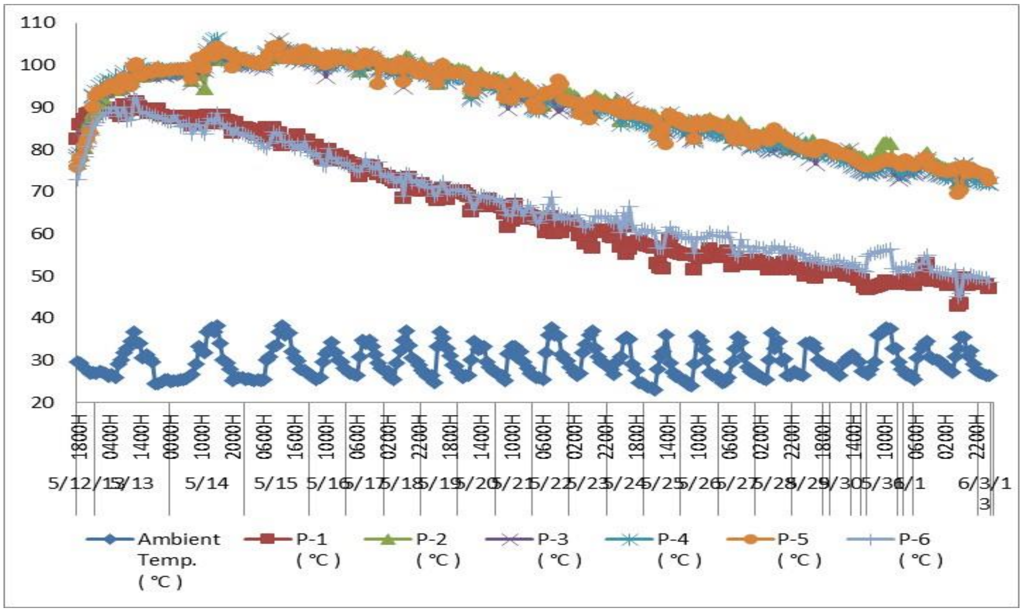

Fig. 1: Actual temperature monitoring on poured concrete mat foundation.

This work aims to determine the strength of high-early strength concrete; if subjected and simulated with the same thermal conditions by the application of isothermal sealed curing of representative sample specimen. Background information was provided including temperature readings gathered for the whole monitoring period to be used and subjected to the same actual temperature readings.

1.1. Review of Related Literature

High-early-strength concrete, as per ACI 116R refers to a type of concrete in which; with the use of high-early strength cement or admixtures, attains a given level of strength earlier than normal concrete does. In local practice, this pertains to the use of high range retarding water-reducing superplasticising admixture, which was usually mixed during concrete batching. It's classification under Philippines Department of Public Works and Highways blue book is Type 'G': Water-reducing, High Range, and Retarding Admixtures [5]. The use of this type of admixture results in concrete mix with excellent workability for high-slump pumpable concrete as well as a very low water to cement ratios formulated for high strength concrete and high-early strength concrete.

Although perfectly suitable and ideal for bulk concrete structures with massive steel reinforcing requirements, the low water to cement ratio exhibited by the concrete mix results in a significant isothermal induced hydration of cementitious materials, and is more pronounced on mass concrete structure. But considering that concrete strength is being a secondary concern in the design of mass concrete structures, the more applicable term to employ is reinforced mass concrete.

It is imperative to mention that for reinforced mass concrete, the reinforcement are utilized to restrict the size of cracks that would otherwise occur [3]. Yet for massive reinforced structures such as foundations, limiting possible crack widths become increasingly difficult and impractical thru the utilization of reinforcement with the corresponding increase of size and dimension of the structure. For this reason, the concrete structural strength becomes of primary importance and significance.

Numerous studies and publications were made focusing on the effects of volume change (shrinkage) by chemical process in the performance and durability of concrete structures, and yet relatively little information were available on concrete strength correlation for temperature above 60°C. ACI 209R describes the predictive effect of temperature changes on concrete performance. The change in material properties due to cement hydration such as creep and shrinkage has shown that apparent maximum creep rate occurs between 122 and 176°F (50 and 80°C) [6]. From 122 to 212°F (50 to 100°C), creep strains then continue to increase with temperature even reaching four to six times the room temperature, although no definitive studies were available above 212°F (100°C).

Results obtained first hand by the author from actual temperature recordings from some foundation (mat foundation for turbine-generator and tied foundation for a chimney pedestal) and superstructure (turbine-generator equipment support) had shown that in actual situation, relative curing temperature of high-early strength concrete may be beyond what had been expected, even after considering recommended controls to lower temperature placement and limit temperature variations.

Sufficing to early simulation scenario for a 1.00m cubic meter concrete block using the same design mix, has shown familiar trend (as observed on some similar studies) recommending maximum concrete temperature after placement not exceeding the range of 155 to 165°F (68 to 74°C) [7], which were the basis on recommending the use of the high-early strength design mix due to favourable temperature readings gathered. Beyond this range, it was found out that deleterious expansion above 158°F (70°C) were cited based on laboratory testing of mortar prisms which may lead to long term primary damage mechanisms for concrete, commonly referred to as DEF (Delayed Ettringite Formation) [8] once penetrated by moisture. This paper focuses on the relative concrete strength condition within the scope of the available temperature data sets gathered by simulating actual temperature condition in an isothermal environment.

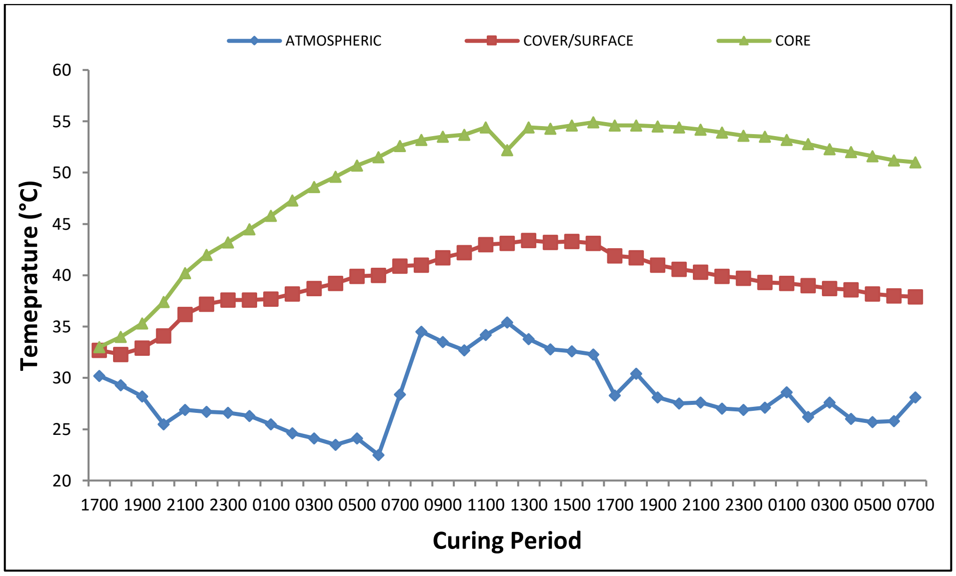

Fig. 2: Simulated temperature monitoring on a 1.00m x 1.00m concrete block.

1.2. Statement of the Problem

Case of isothermal sealed curing where previously studied relative to the application of high early-strength concrete at laboratory scale, with typical focus on the measurement of volume changes in concrete as controlling factor on bulk/mass concrete strength and durability. While it was known from similar studies that increasing curing temperature also increases one-day strength and its 28-day strength decreases and is generally lower at later ages, these were simulated at normal conditions where unsystematic temperature dependency with autogenous and chemical reaction is not being given attention, more so with curing temperature reaching alarmingly above 100°C based from previously completed temperature monitoring undertaken by the author on actual massive concrete foundation of structures.

From these specific prevailing conditions encountered, the use and application of high-early-strength concrete specifically on massively reinforced structure needs to be revisited and studied to have a clear understanding on the effect of isothermal sealed curing caused by autogenous and chemical reactions of cementitious materials on concrete, and whether this unusually elevated temperature readings has a debilitating effect on the durability of the structure as well as the purpose of ensuring early intended use of the structure.

1.3. Significance of the Study

Massive reinforced concrete pouring of structures generates heat as the cementitious materials hydrate during curing process, it is imperative to manage this temperature increase to prevent damage, minimize any untoward delays and to meet needed project specifications. Although there are already proven effective guidelines on handling mass concrete including needed controls and recommended specifications, this study aims to determine and assess the effect of chemically-induced temperature increase during curing process specifically when subjected to above expected temperature readings.

Since the use of high early-strength concrete is of usual practice especially for civil works nowadays, the expected output from this work will surely be of great importance in specifying whether current quality control preparations in dealing with this type of concrete for reinforced bulk structures; is sufficient enough to achieve the desired specifications relating to concrete strength prior to its intended service.

1.4. Objectives

With reference to the actual gathered temperature monitoring data sets on reinforced bulk concrete pouring of mat foundation structure, the primary objective of this work is to determine through a controlled laboratory testing the effects of isothermal curing on the compressive strength of the concrete sample by simulating the actual temperature readings gathered previously on the same high early-strength concrete design mix. This isothermal condition is intended to be replicated and achieved through the utilization of the usual equipment set-up for buoyancy method (autogenous shrinkage test), although salient emphasis shall be relating to compressive strength of concrete cylinder samples. Secondly, the expected compressive strength results generated at specified age will then be compared on the compressive strength of similar samples from the same batch, which were subjected to standard curing of samples using ASTM C31 [4].

1.5. Scope and Limitation

The extent and scope of this work shall be specifically for the sampling and testing of 5000psi (35MPa) at 3-day high-early strength concrete design mix. Available actual temperature records at the time of this study only apply to this specific age of concrete (5000psi/35MPa at 3 days). Furthermore, water to cement ratio shall be specific/lower than 0.32, which is within the range for which isothermal (chemical reaction) curing is expected to occur (< 0.42 w/c ratio). The size of concrete cylinder sample is also reduced proportionately to 50mm diameter x 100mm height since this will be enclosed and sealed in a flexible rubber membrane for sample sets to be subjected to isothermal curing.

Expected actual compressive strength testing of these concrete cylinder samples shall be undertaken at 1, 3, 7, 14, 21, 28 and 56-day period. Although autogenous and chemical (volumetric) shrinkage is expected to impact to the result of the readings to be gathered, this study shall limit only on the visual observation whether there is presence or absence of cracks due to volumetric shrinkage, before (sample condition) and after (type of failure and presence of probable cracks) breaking of samples.

1.6. Conceptual Framework

High-early strength concrete when utilized in concrete pouring of bulk foundations are usually designed with the use of high performance/high strength concrete admixture which is characterized by a low water to cement ratio. As a consequence, self-desiccation takes place leading to shrinkage of concrete paste. The moisture is lost either through evaporation (drying shrinkage) or internal reactions (autogenous shrinkage). But probable generation of cracks due to cement paste hydration is somehow minimize/avoided by the presence and design of steel reinforcement. With volumetric shrinkage treated reticently, correlation with the chemical reaction to the strength of concrete should be factored henceforth.

For isothermal curing to be simulated with the actual temperature condition expected, the membrane method shall be employed with confining thermal bath made of mineral oil. This simulated curing ensures that no moisture transfer is permitted within the environment, thus direct correlation of concrete strength can be determined relative to the internal chemical reaction either due to evaporation or autogenous shrinkage.

2. Methodology

2.1. Materials

Preliminary source of temperature recording data sets were undertaken by the author on actual concrete pouring for a turbine-generator and chimney flue foundation, elevated superstructure of turbine generator and simulated curing on a one-cubic meter concrete block using high-early strength concrete mix 5,000 Psi (35MPa) @ 3 days. Based from this actual temperature monitoring readings (showing uniform trending on temperature variations above 100°C) taken at different part of the structure, the temperature data sets for the turbine-generator mat foundation shall serve as the reference temperature reading on subsequent simulated monitoring covered by this work. Correspondingly, the concrete design mix with ideal design strength of 5,000 Psi (35 MPa) at 3 days were adopted with relative adjustments on material proportions as recommended by ACI 211.1; and based from the actual quality test results of major constituent materials including cement, fine and coarse aggregates, and admixture.

The concrete constituent materials, testing equipment and laboratory apparatus including laboratory and concrete mixing facilities were sourced and arranged with Tokwing Infinite Batching Plant situated at Mindanao Avenue, Quezon City, Philippines. The conduct of materials and concrete sampling was directly held at the confines of laboratory premises since concrete samples were expected to have early-strength development and was according to ACI 211.1 [9]. ASTM C172 [10] shall be applied in selecting appropriate sample size through wet sieving to obtain the desired ratio and proportion relative to the size of concrete cylinder sample (57mm Ø). Provision for needed thermal bath for membrane method curing measurement was set-up and installed prior to concrete sampling. Thermostat equipment controller has reading accuracy of 0.1°C with regular readings encoded once concrete cylinder samples were already in-place.

2.2. Testing

A digital thermostat controller were operated with attach thermocouple device submerged at the center of the paraffin/mineral oil bath, this device ensures that temperature reading has simulated the encoded data sets. Once concrete cylinder samples tightly wrapped in a flexible rubber membrane was prepared and immersed in the thermal bath, regular encoding of desired temperature readings were undertaken. Expected duration was undertaken for a period of 56 days. Simultaneously undertaken with this procedure is the laboratory curing of similar identical samples prepared as per ASTM C31 [4]. Each representative samples (minimum set of 3 concrete cylinder) were tested at specified 1, 2, 3, 7, 14, 21, 28 and 56-days curing period to determine respective compressive strength of concrete.

In order to establish direct correlation with the expected design strength of 5000Psi (35MPa) at 3 days, a standard cylinder mold of 100mmØ (4in. Ø) was used to identify the strength requirements at specified days (1, 3, 7, 14, 21, 28 & 56 days). This served as a basis for the concrete strength profile specific to the concrete mix design since the reduced sample size were due to the limitations on commercially available flexible rubber membrane that was utilized during testing.

2.3. Data Analysis

A set of comparable data were tested and generated, the first set includes compressive test results for isothermal curing of cylinder samples and the second set are the regular compressive test results using ASTM C31-Standard Practice for Making and Curing Concrete Test Specimens in the field [4]. Tables and charts were then generated based from the actual compressive readings from the UT machine at specified age of concrete: 1, 2, 3, 7, 14, 21, 28 and 56-days. A plot of temperature recordings and relative concrete strength versus period of observation shall be prepared to investigate these findings.

3. Results and Discussion

Actual monitoring and testing of prepared concrete cylinder samples corresponding to specific age of concrete were plotted as shown in Figure 3. Using standard concrete cylinder mold (100mmØ), the recorded strength at 3 days had reach an average of 52.17MPA (7,300Psi) and has exceeded the concrete design strength of 35MPa (5,000Psi) at 3 days. The noted increase in concrete strength at 3 days was taken at an actual water-cement ratio of 0.23 against a design w/c ratio of 0.26, where the concrete mix at this instance was still workable. The 28-day concrete strength has reached an average of

67.63MPa (9,500 Psi) while the 56-day strength resulted to 73.73MPa (10,300 Psi) and is further increasing based from the figure.

Corollary to this, the 57mmØ concrete cylinder sample size had also exhibited the same trend in strength development but notably in a much reduced average compressive strength values of 17.76MPa, 22.87MPa and 24.18MPa for 3, 28 and 56-day age. Although the difference in strength values was notable, when compared with the reduction in effective area of test diameter (by ratio), it would sufficiently give the same equivalent results and trend.

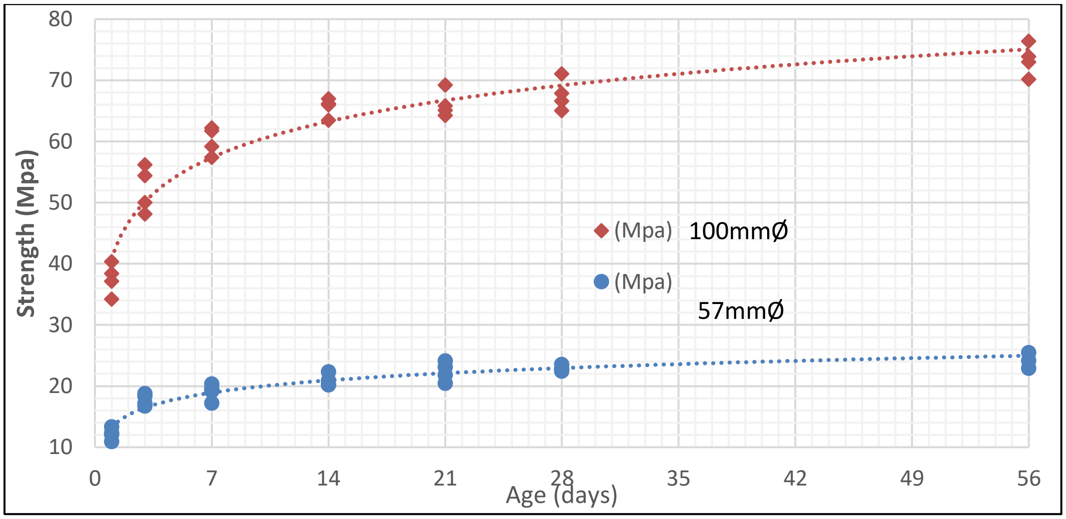

Fig. 3: Plot of Normal (100mmØ) and Reduced (57mmØ) Cylinder Samples.

Digitization of temperature profile as shown in Figure 4 represents the correlation between increase in temperature and corresponding increase in strength of the samples subjected to the same isotherm condition. The increase in strength, although not as abrupt as compared to the heat gained (103.4°C at 3 days) by the concrete samples during curing period, reflects to interdependency of the increased strength of the samples to its curing temperature. But as the temperature normalizes, also noticeable is the corresponding decrease in temperature from peak strength of 33.64MPa (4,800 Psi) at 14 days.

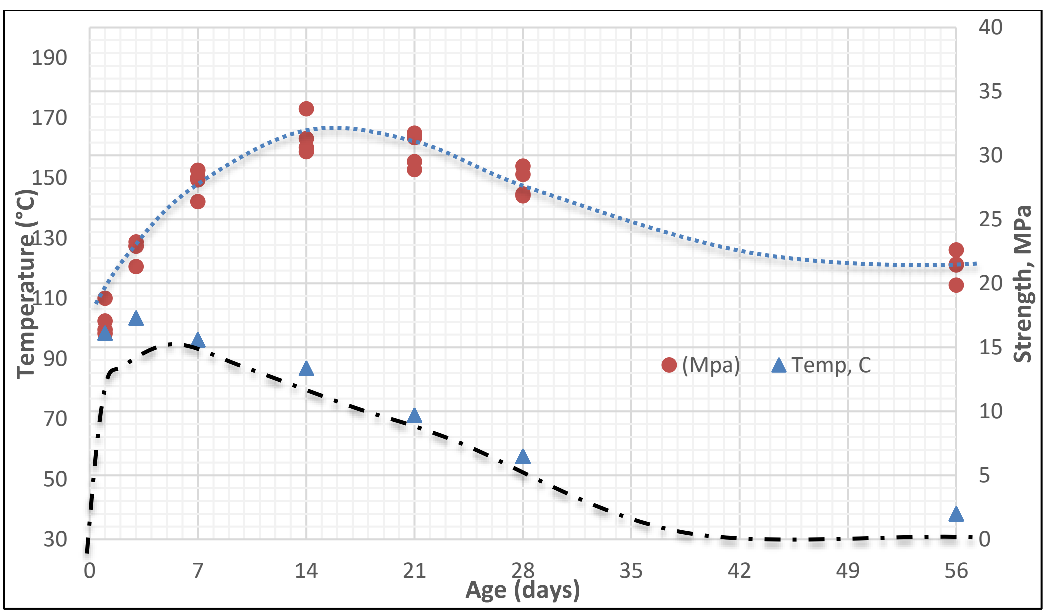

Fig. 4: Plot of Temperature Control & Compressive Strength (Isothermal)

Preliminary comparison of tabulated concrete strength results for both normal and isothermal cured reduced cylinder sample size results in a converging trend line pattern as shown in figure 5 starting from a notable difference of 4.92MPa average concrete strength in day 1 alone. While on the 3rd, 7th and 14th days, the nominal variation in average strength difference had widened by an average of 27%, 46, and 50% (4.83MPa, 8.81MPa and 10.54MPa) respectively. A downward trend on strength development was observed at 21, 28 and 56 days at 35%, 22% and -12% (7.99MPa, 5MPa & -2.84MPa) as compared with normal cured samples.

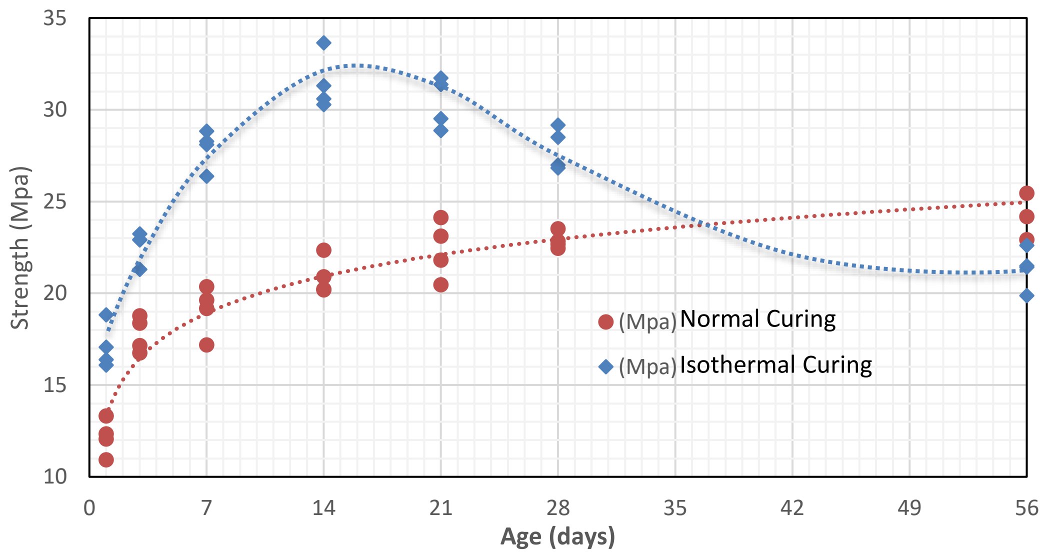

Fig. 5: Plot of Isothermal and Normal-Cured (57mmØ Cylinder Samples)

4. Conclusion

Results of subsequent compressive strength test on sets of concrete cylinder samples at specified age from these research work gives a comprehensive understanding on the effect of isothermal curing on the compressive strength of concrete at early age as compared with regular laboratory-controlled concrete samples.

This eventually gives us a clearer indication and analysis of what we essentially expect, once the use of high-early strength concrete exceeded maximum temperature threshold as recommended by related literature and technical specifications [11][12]. Moreover this work gives us a good assessment that inherent chemical reaction and heat generation when not properly controlled, will adversely impact the strength of concrete samples at early age.

More research is needed on the effects of early-age chemical shrinkage, self-desiccation and delayed ettringite formation (DEF) [8] at higher curing temperature above 70°C to determine long-term adverse effects on the strength and durability of concrete as well as the performance on the foundation of structure, which on this case is critical; since the mat foundation for a turbine generator of a power plant is subjected to continuous vibration.

Acknowledgements

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