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***Research paper***

# Effects of Curing Condition and Curing Period on the Compressive Strength Development of Plain Concrete

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***A b s t r a c t***

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*Curing,*
*Humidity,*
*Temperature.*

This paper presents the results of an experimental study on the effects of curing methods and curing ages on the compressive strength development of ordinary Portland cement concrete in a tropical environment. Fifteen (15) concrete cubes each were cured by immersion in potable water, immersion in lime water, covering with wet rug, covering with plastic sheets and air-drying. For each of these curing methods, the average compressive strength of concrete cubes was determined after 3, 7, 14, 28 and 90 days curing periods. The results obtained discourages the use of curing by air-drying method and also suggests limiting the use of the other curing methods to 28-days period. Generally, the highest compressive strength was obtained for concrete cured by immersion in lime water.

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## 1. Introduction

Concrete is the single most extensively used man-made material in the world. It has been used for the construction of buildings, bridges, dams, pavements, sewerage systems, tunnels, waste containment systems, etc. One of the most important properties of concrete is its compressive strength. It is a major indicator of its quality. Thus, it is usually desirable that concrete is made to develop its maximum attainable compressive strength. Curing is one process that facilitates the maximization of its potential strength. Curing ensures that concrete experience continued hydration, leading to its continued strength gain. Continued hydration is achieved by maintaining satisfactory moisture content and temperature within the concrete for a sufficient period of time. Aside accelerating the strength gain of concrete, curing also improves its durability, water-tightness, abrasion resistance, volumetric stability, resistance to freezing and thawing, resistance to de-icing chemicals; minimizes creep, reduces powdery deposition on concrete surfaces and prevents crazing [1-3]. Curing is a process that typically follows consolidation and finishing processes in the order of operations for the production of concrete. It should normally start after the final set of the cement in order to avoid drying shrinkage and consequently, the development of cracks.

Two main categories of methods for curing concrete are: those that maintain availability of water and those that minimize the loss of mixing water from concrete by sealing its exposed surfaces. Ponding or immersion, sprinkling or fogging, and use of wet coverings are methods used to maintain the availability of water for curing concrete. The use of membrane-forming compounds, impervious paper or plastic sheets and leaving forms in place are methods used for preventing loss of water from concrete. It is not advisable to use the methods of preventing loss of water for concrete with water-cementitious materials ratio of less than 0.4. This is because the concrete does not have sufficient water for complete hydration. It was suggested that special precaution needs to be taken if the environmental temperature for curing is higher than 30°C or less than 10°C [4] and that curing water should not be more than about 11°C cooler than the concrete, to prevent thermal stresses that could result in cracking [5]. To determine which curing method(s) to adopt, it is necessary to consider factors such as the availability of curing materials, the size and shape of the structure, economics, environmental conditions, supervision, in-place versus plant production and aesthetics [1].

Various research efforts have been made to investigate the influence of curing conditions or methods on the compressive strength of plain and blended cement concrete [6], high performance concrete [7,8], self-compacting concrete [9-11], concrete under hot weather conditions [12], ordinary concrete [13-17], and concrete containing supplementary cementitious materials [18-25]. Raheem et al. [26] investigated the effects of curing by immersion in water, spraying with water, covering with plastic sheet, covering with wet burlap, using moist sand, and laboratory air-drying, on the compressive strength of concrete. The concrete used had a mix proportion of 1:2:4 (cement:sand:granite) and was cured for 3, 7, 14, 21 and 28 days. The researchers found that concrete cured using moist sand gave the highest 28-day compressive strength.

As there continues to be more and more evidence that the world is getting warmer, with one of the effects being that dry areas become drier and wet areas become wetter, there is need to continually assess the effectiveness of the various curing methods in various locations around the world. This change in climate has the potential of making those curing methods that were previously identified as being less-effective in aiding maximum attainable strength development of concrete, become more suitable for particular climatic conditions. This research effort is aimed at investigating and comparing, in a tropical climate such as that of Nigeria, the compressive strength development of concrete cured by immersion in potable water, immersion in lime water, covering with wet rug, covering with plastic sheets and air-drying, for 3, 7, 14, 28 and 90 days curing periods.

## 2. Materials and methods

### 2.1. Materials and preparation

An ordinary Portland cement (ASTM Type I), obtained commercially; river sand having its particles size ranging from 0.075 to 4.75 mm; and crushed granite having a maximum size of 20 mm; were utilized for production of the concrete used for this research work. Potable water was used for both mixing and curing of the concrete. Saturated lime solution was prepared from commercially-obtained powdery-lime. Hydrated lime was mixed with water in a curing drum such that the excess was allowed to settle at the bottom of the drum, in order to keep the solution saturated with lime throughout the entire curing period.

Pre-washed and pre-moist rug was used as a wet covering for concrete cubes designated to be cured by this method. Transparent nylon, 0.1 mm thick, was wrapped around the concrete cubes designated for curing by covering with plastic sheet. The edges of the sheet were made to overlap and were fastened with waterproof tapes. Steel and plastic tanks containing water and saturated lime water, respectively, were used for curing the concrete cubes designated for the respective curing methods.

### 2.2. Experimental work

Sieve analyses of the sand and granite were carried out to determine their particle size distribution. The concrete used was batched by volume, in a ratio of 1:2:4 (cement:sand:granite). A water-cement ratio of 0.5 was used. The concrete was mixed in a tilting drum mixer for 3 minutes. The consistency of the concrete was determined by carrying out slump test. Air content in the concrete was determined using pressure method apparatus. The concrete cubes (150 x 150 x 150 $mm^3$) were cast using steel moulds. The cubes were removed from the moulds 24 hours after they were cast. They were labeled appropriately, with respect to the curing methods used and the dates their compressive strengths were to be determined. Immediately after, the cubes were cured using the designated curing methods, and for the designated periods. Except for concrete cubes cured by covering with wet rug, all other curing methods were done within the laboratory. Curing by covering with wet rug was done outdoors because water was poured regularly, during the curing period, on the rug in order to keep it wet. Compressive strengths at ages 3, 7, 14, 28 and 90 days were determined for each of the curing methods used. The average of three compressive strength results, for each curing period and for each of the curing methods, was determined. The compressive strength of concrete cubes was determined in compliance with BSI [27], using YES-2000 digital display compression machine.

## 3. Results and discussion

### 3.1 Environmental conditions

Temperature and moisture, which are very important when considering concrete curing, usually vary except in controlled environments. Figure 1 presents a plot of the mean daily temperatures and the mean daily relative humidity in the laboratory, during the entire curing period. During this period, the mean daily temperature and relative humidity ranged from 27.2 to 30.3°C and 56 to 83%, respectively.

### 3.2 Material characterization

Particle size distribution for the sand and granite (Figure 2) were obtained from the results of their sieve analyses. The sand used had a larger proportion of its particles falling within the medium to coarse range. Its uniformity coefficient and coefficient of curvature were calculated to be 2.8 and 0.9, respectively. According to the Unified Soil Classification System, uniformity coefficients less than 6 for sand indicate that the particles were of uniform size (poorly-graded). Coefficient of curvature outside a range of 1 to 3 indicates the absence of certain grain sizes. For the granite, its uniformity coefficient and coefficient of curvature were calculated to be 1.9 and 1.1, respectively. According to the Unified Soil Classification System, uniformity coefficients less than 4, for gravel-sized particles, indicate that the particles were poorly graded.

The air content and average slump for the concrete used were ascertained to be 1.5% and 27 mm, respectively.

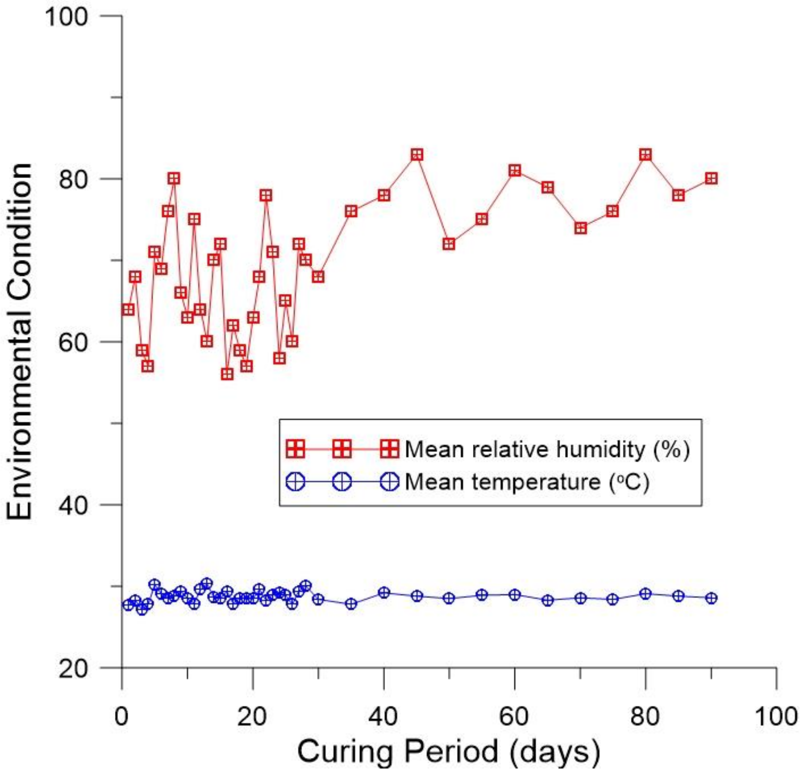


Fig. 1. Relative humidity and temperature variation

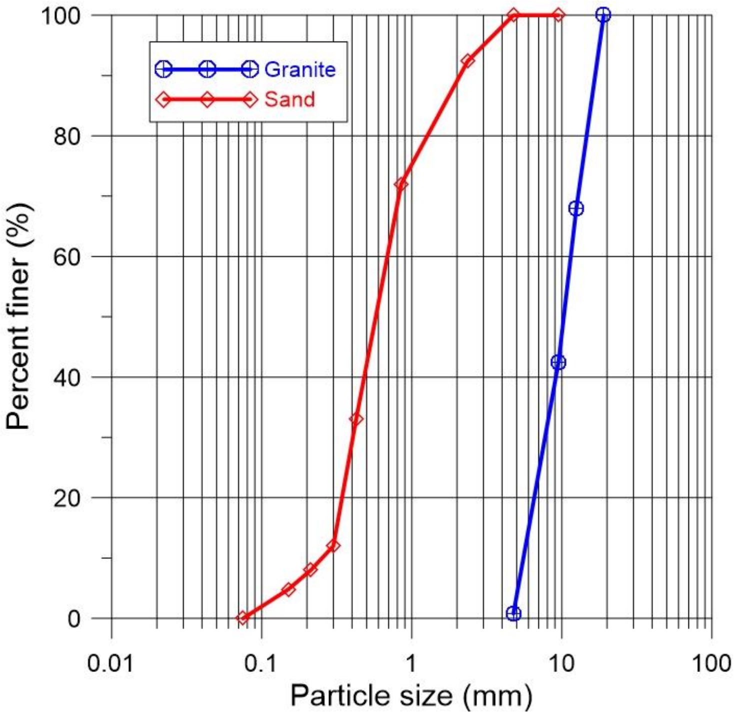


Fig. 2. Particle size distribution of sand and granite

### 3.3 Compressive strength

#### 3.3.1 General comparison

A summary of the results of compressive strength of the concrete cubes, at ages 3, 7, 14, 28 and 90 days, and for each of the curing methods, is presented in Figure 3.

From Figure 3, the curves showing the compressive strength development of concrete cubes cured by: immersion in lime water; covering the cubes with plastic sheet; and immersion in water, were observed to be similar to those typified in concrete technology textbooks [1, 3]. However, the curves for the compressive strength development of those cubes cured by covering with wet rug and by laboratory air-drying deviated from expectation. It was expected that, after 28 days of curing, these curves would become nearly flat. Zhang and Zhang [28] found out that the degree of cement hydration in concrete exposed to a tropical environment increased with curing age but that the increase beyond 28 days was not significant. With no significant increase in cement hydration after 28 days curing period, it was expected that the compressive strength will not also be significant after 28 days of curing. Magnifying the curing period before this deviation was experienced (Figure 4), shows that concrete cubes cured by immersion in lime water and those cured by wet-rug covering developed the highest and least compressive strength, respectively. While concrete cured by immersion in lime and that covered with a plastic sheet had their compressive strength meeting the minimum specified 28 days compressive strength (20 $N/mm^2$) for the particular mix design used, others had their 28 days compressive strength being less than 20 N/mm$^2$.

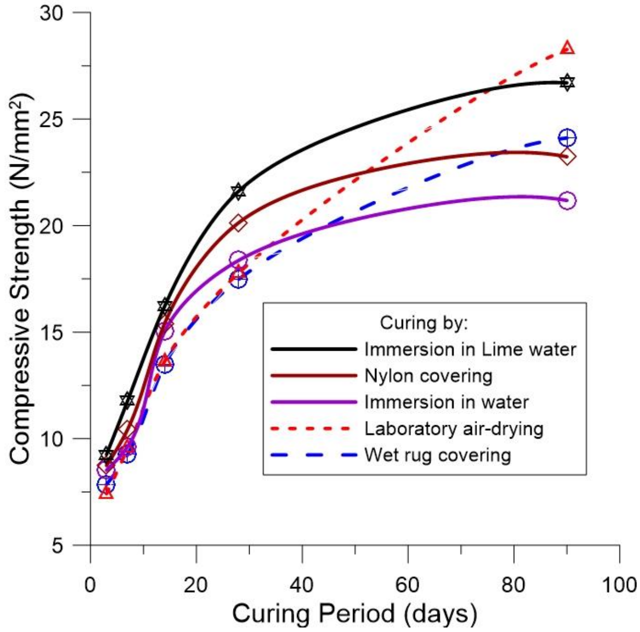


Fig. 3. Variation of compressive strength with curing period

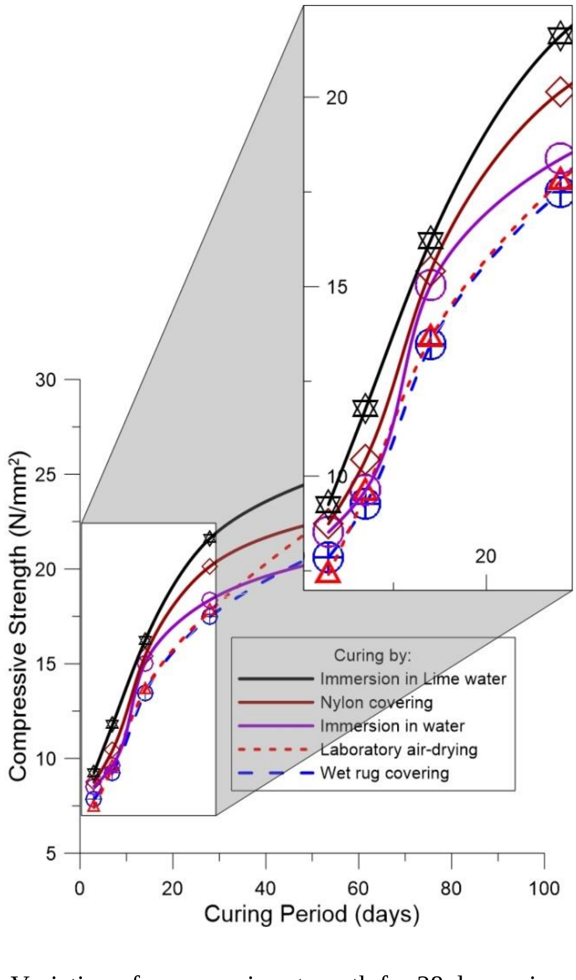


Fig. 4. Variation of compressive strength for 28 day curing period

Arranging the curing methods in a descending order of compressive strength development gives: immersion in lime water; covering with plastic sheets; immersion in potable water; laboratory air-drying; and covering with wet rug. Surprisingly, concrete cured by covering with wet rug had its strength being less than those allowed to be air-dried in the laboratory. This may be attributed to the outdoor conditions which the concrete covered with wet rug was exposed to. Gayarre et al. [29] found out that concrete cured outdoor had lower compressive strength, compared to that cured indoor.

The portion of the curves in Figure 3, after the 28-day curing period, shows that the compressive strength of the air-dried concrete cubes developed the highest compressive strength. Also, cubes cured by covering with wet rug rapidly gained strength, such that they developed higher 90 days compressive strength than those cured by immersion in water and those covered with plastic sheet for the same period. These rapid increases in compressive strength of concrete cubes cured by air-drying and wet-rug covering may be attributed to a general increase in the relative humidity, after 28 days of curing.

### 3.3.2 Relative compressive strength per curing period

The compressive strength of concrete cubes cured for 3 days, using the various curing methods and relative to the average compressive strength of those cured in lime water, is presented in Figure 5. The average compressive strength of concrete cubes cured in lime water was highest for this curing period. Newbold and Olek [30] similarly found that concrete cured in lime water developed the highest compressive strength, after comparing the compressive strength of air-cured, sandpit-cured and lime-bath cured concrete cube for a period of 3 days.

Relative to the compressive strength of concrete cured in lime water, Figure 5 shows that the differences in the relative compressive strength for each of the concrete cubes cured by air-drying, covering with wet rug, immersion in water and covering with plastic sheet are 20%, 15%, 8% and 5%, respectively. A comparison of these results with those of the 3 days compressive strength presented by Raheem et al. [26] (after it was further analyzed) showed that the compressive strength of concrete immersed in water, for both analyses, was higher than that of those cured by wet covering and air-drying. However, results of Raheem et al. [26] show that the compressive strength of concrete cubes cured by immersion in water was higher than the compressive strength of those cured by covering with plastic sheet.

For each of the 7-, 14- and 28-day curing periods, the compressive strength of concrete cubes cured using the various curing methods and relative to the average compressive strength of those cured in lime water, is presented in Figs. 6, 7 and 8, respectively.

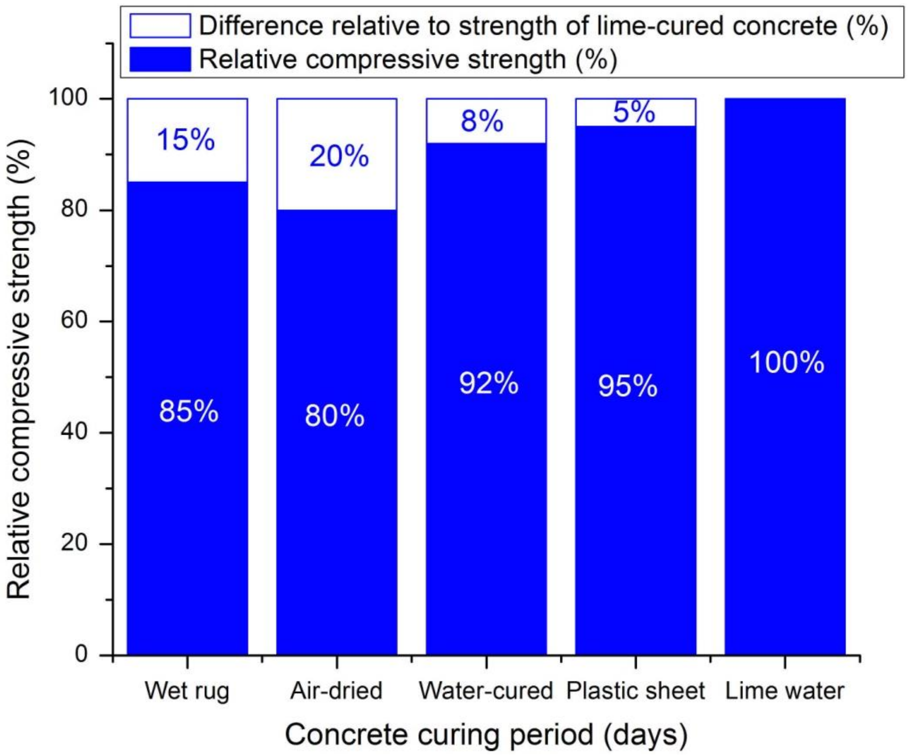


Fig. 5. Relative compressive strength versus curing methods for the 3-day curing period

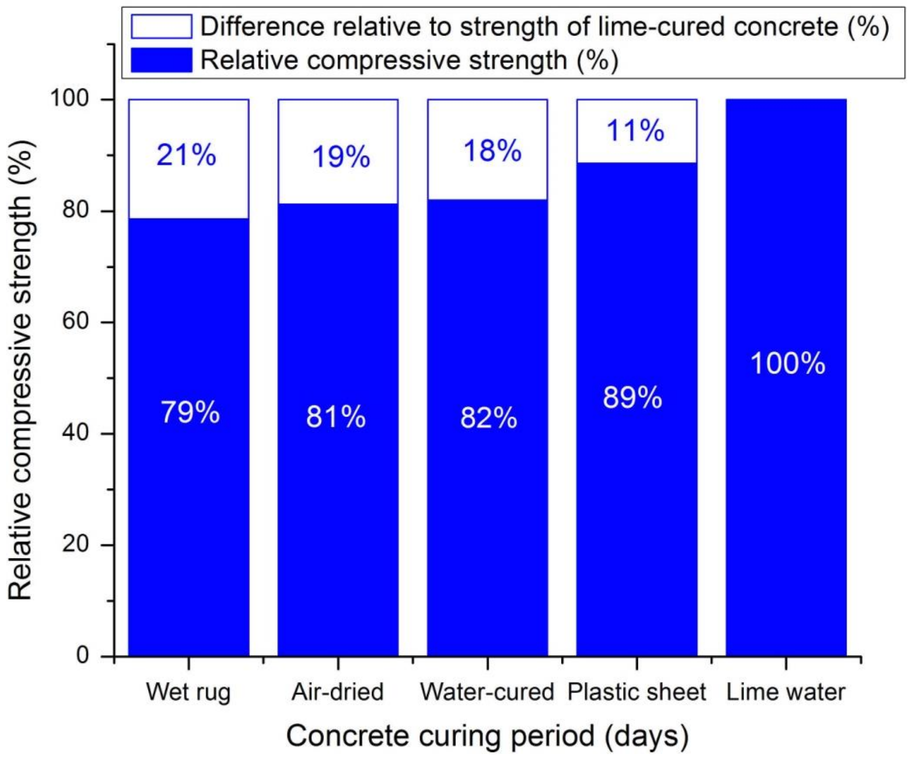


Fig. 6. Relative compressive strength versus curing methods for the 7-day curing period

Figs. 6, 7 and 8 show that concrete cubes cured by covering with wet rug developed the least compressive strength. Arranging the curing methods in a decreasing order of the differences in their compressive strength relative to that of concrete cured in lime water gives: covering with wet rug; laboratory air-drying; immersion in water and covering with plastic sheets. This result is not similar to that obtained by Raheem et al. [26] for the 7-, 14- and 28-day curing periods, except that concrete cubes cured by wet covering also had the least compressive strength for the 7- and 14-day curing periods.

The compressive strength of concrete cubes cured for 90 days, using the various curing methods and relative to the average compressive strength of those cured in lime water, is presented in Figure 9.

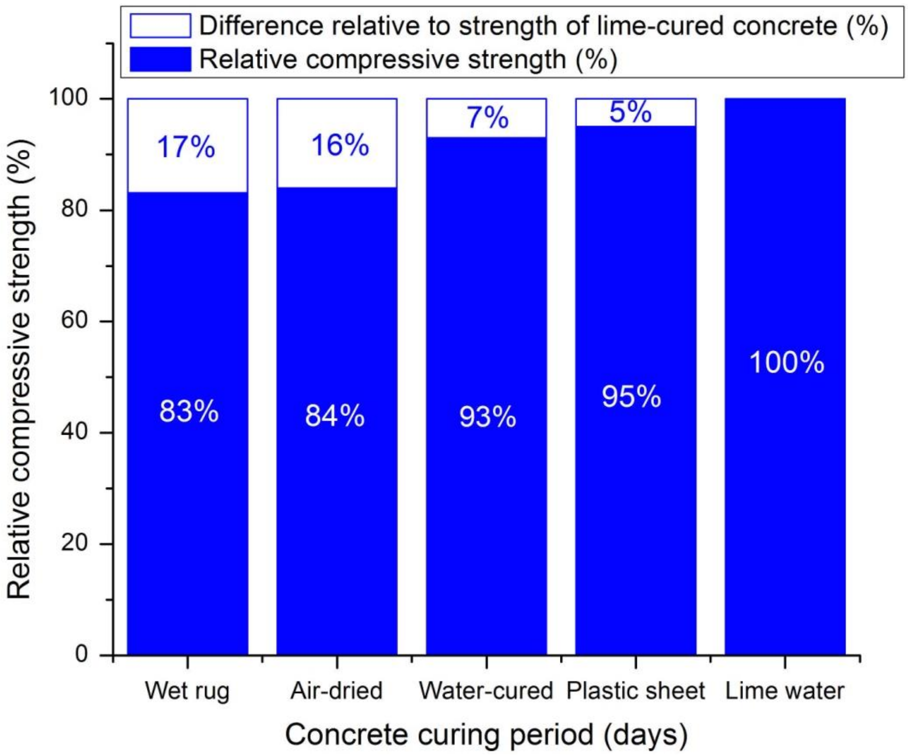


Fig. 7. Relative compressive strength versus curing methods for the 14-day curing period

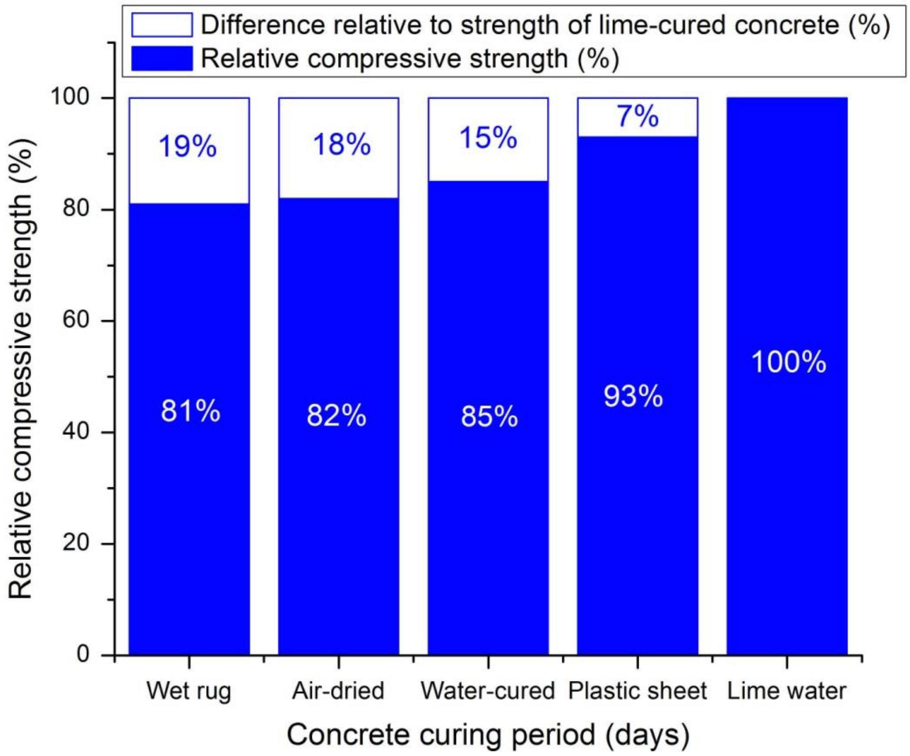


Fig. 8. Relative compressive strength versus curing methods for the 28-day curing period

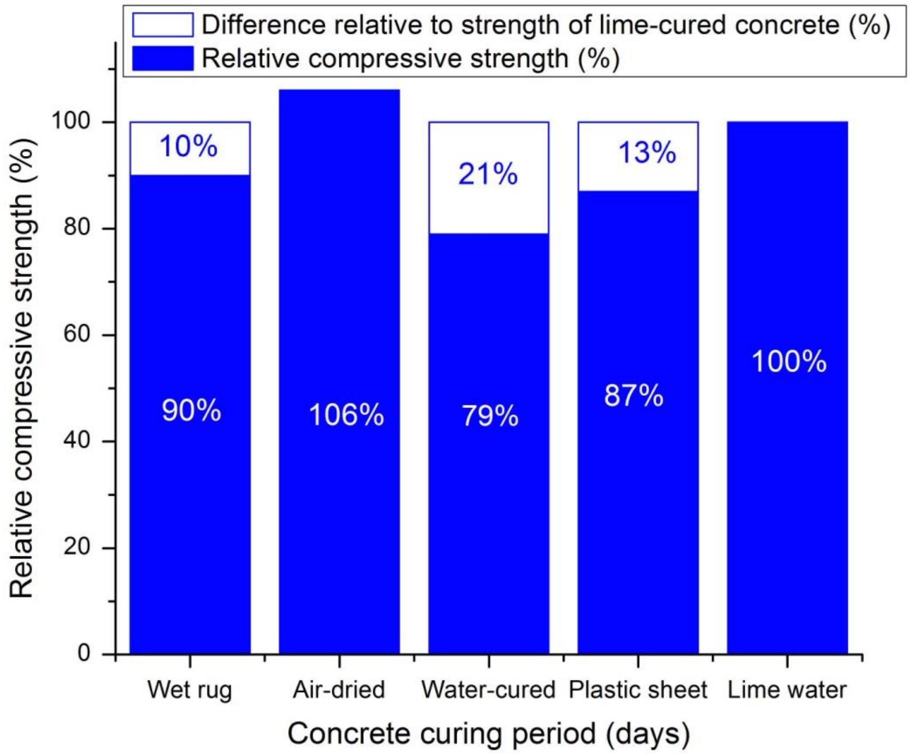


Fig. 9. Relative compressive strength versus curing methods for the 90-day curing period

Figure 9 shows that concrete cubes cured by air-drying in the laboratory and by immersion in water developed the highest and least compressive strength, respectively. Relative to the compressive strength of concrete cured in lime water, Figure 9 shows that the differences in the relative compressive strength for each of the concrete cubes cured by immersion in water, covering with plastic sheet and covering with wet rug are 21%, 13%, and 10%, respectively. It also shows that the relative compressive strength of concrete cubes cured by air-drying increased by 6% for this curing period. This result agrees with the popularly acceptable standard of limiting curing of concrete to 28 days.

### 3.3.2 Relative compressive strength per curing method

For concrete cubes cured by immersion in lime water; covering with plastic sheet; immersion in water; covering with wet rug and laboratory air-drying, the compressive strength for each curing period relative to their compressive strength obtained after the 28-day curing period, is presented in Figs. 10, 11, 12, 13 and 14.

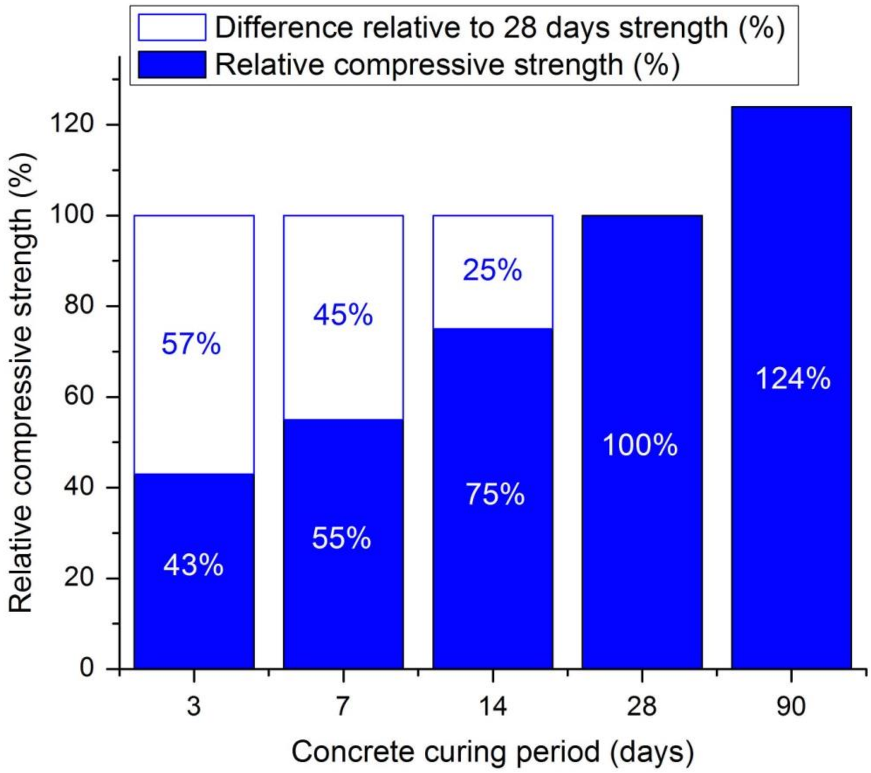


Fig. 10. Relative compressive strength versus curing periods for the concrete immersed in lime water

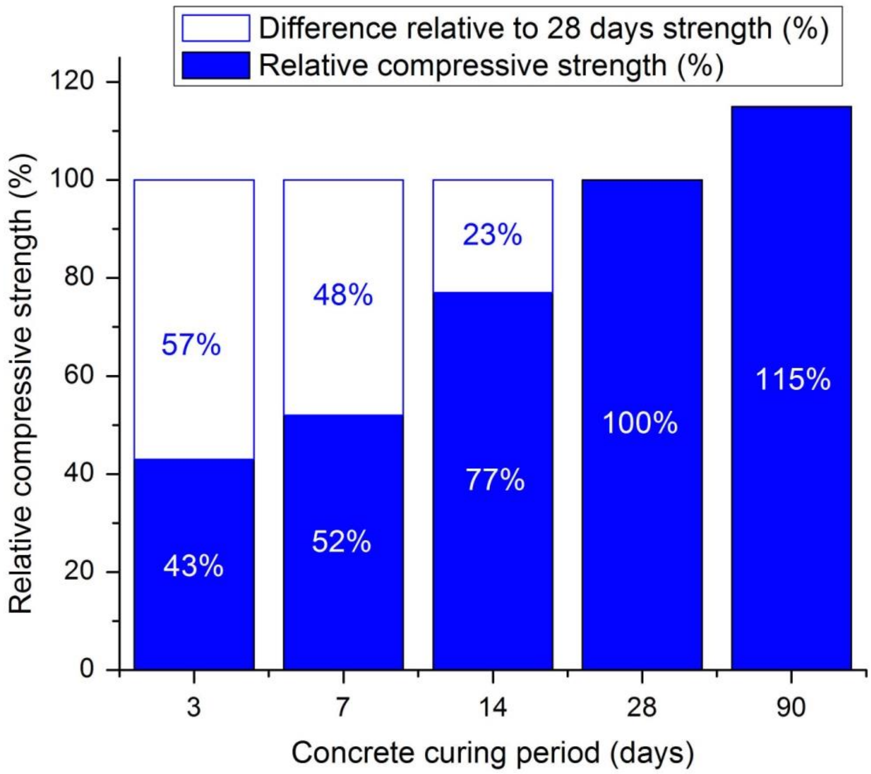


Fig. 11: Relative compressive strength versus curing periods for the concrete covered with plastic sheet

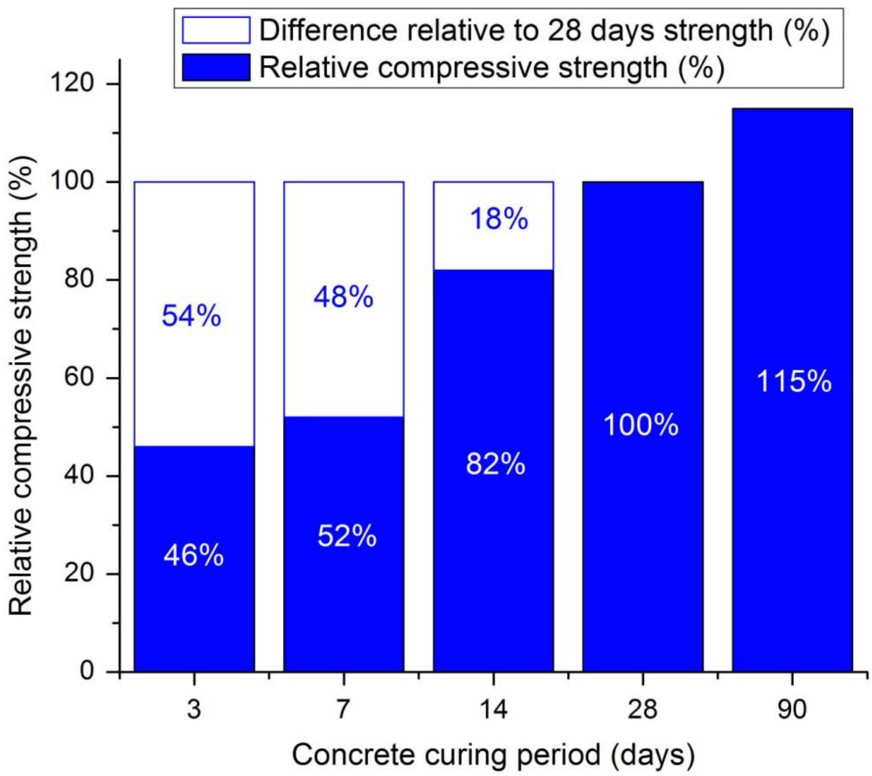


Fig. 12. Relative compressive strength versus curing periods for the concrete immersed in water

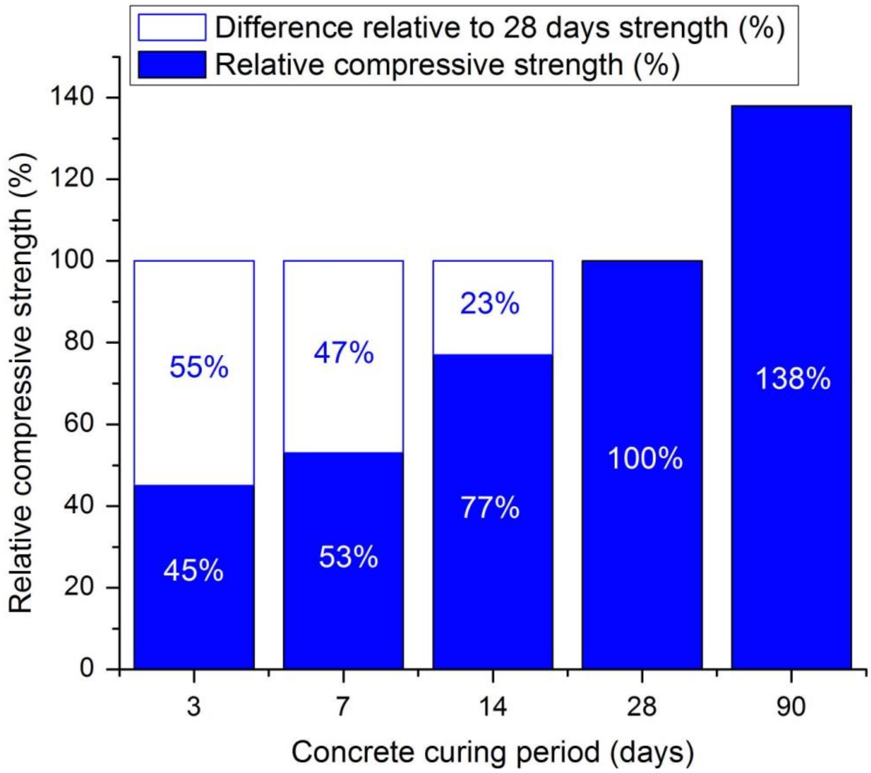


Fig. 13. Relative compressive strength versus curing periods for the concrete covered with wet rug

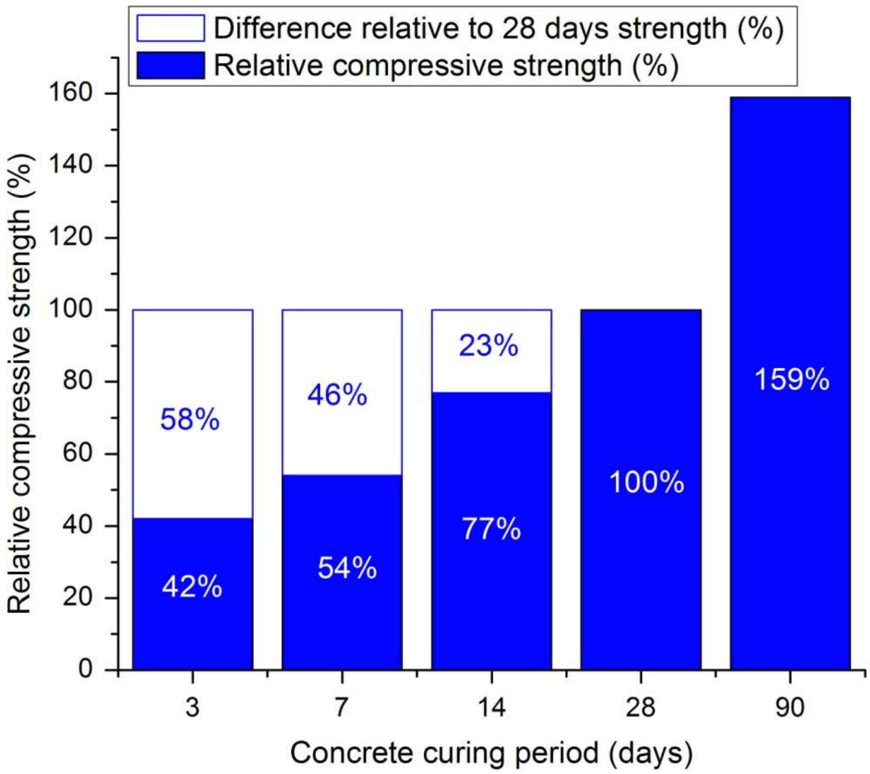


Fig. 14. Relative compressive strength versus curing periods for air-dried concrete

Figs. 10, 11, 12, 13 and 14 show progressive increments in the compressive strength of concrete with increasing curing period, for all the curing methods. Relative to the 28 days strength of concrete cubes cured in lime water, Figure 10 shows that the differences in the relative compressive strength (relative to the 28 days strength of concrete cubes cured by immersion in lime water) for each of the 3-, 7- and 14-day curing periods are 57%, 45% and 25%, respectively. It also shows that the compressive strength of concrete cured by immersion in lime water for a curing period of 90 days increased by 24% for this curing period.

Figure 11 shows that the differences in the relative compressive strength (relative to the 28 days strength of concrete cubes cured by covering with plastic sheet) for each of the 3-, 7- and 14-day curing periods are 57%, 48% and 23%, respectively. Analysis of the compressive strength results presented by Raheem et al. [26] for concrete cubes cured by covering with plastic sheet showed that the differences in the relative compressive strength (relative to the 28 days strength of concrete cubes cured by covering with plastic sheet) for each of the 3-, 7- and 14-day curing periods are 35%, 30% and 20%, respectively. Though both research works showed progressive strength development over the curing period, the results of Raheem et al. [26] showed a faster rate of strength development. Also, Figure 11 shows that the compressive strength of concrete cured by covering with plastic sheet for a curing period of 90 days increased by 15%, relative to its 28 days strength.

Relative to the 28 days strength of concrete cubes cured by immersion in water, Figure 12 shows that the differences in the relative compressive strength for each of the 3-, 7- and 14-day curing periods are 54%, 48% and 18%, respectively. Analysis of the compressive strength results presented by Raheem et al. [26] for concrete cured by immersion in water showed that the differences in the relative compressive strength (relative to the 28 days strength of concrete cubes cured by immersion in water) for each of the 3-, 7- and 14-day curing periods are 30%, 27% and 19%, respectively. For concrete cubes cured in water, both research works showed progressive strength development over the curing periods. However, the results of Raheem et al. [26] also showed faster rate of strength development. Figure 12 shows that the compressive strength of concrete cubes cured by immersion in water for a curing period of 90 days increased by 15%. The concrete cubes cured with plastic sheet covering and those cured in water showed similarity in their relative compressive strength development, as seen in Figs. 11 and 12.

Figure 13 shows that the differences in the relative compressive strength (relative to the 28 days strength of concrete cubes cured by covering with wet rug) for each of the 3-, 7- and 14-day curing periods are 55%, 47% and 23%, respectively. It also shows that the compressive strength of concrete cured by covering with wet rug for a curing period of 90 days increased by 38%.

Relative to the 28 days strength of concrete air-dried, Figure 14 shows that the differences in the relative compressive strength for each of the 3-, 7- and 14-day curing periods are 58%, 46% and 23%, respectively. It also shows that the compressive strength of concrete dried in air for a curing period of 90 days increased by 59%. The compressive strength results of Raheem et al. [26] for air-dried concrete was completely different. Its compressive strength after 28 days curing was even lower than that obtained after the 14-day curing. The relative compressive strength development in concrete cubes cured by covering with wet rug (Figure 13) and air-drying (Figure 14) showed similarity. However, concrete cubes air-dried experienced the highest rate of compressive strength development after 28 days curing period. This may be attributed to change in relative humidity, which may have resulted in the slow-down of the hydration process sometime within the 28 days curing period but which later resumed after the 28-day period.

## 4. Conclusions

Based on the research results presented, the following conclusions were drawn:

i. The concrete cubes cured in water and those cured by plastic sheet covering showed similarity in their relative compressive strength development. Also, the relative compressive strength development of concrete cubes cured by air-drying and those cured by covering with wet rug showed similarity.

ii. The use of the following curing methods: immersion in lime water; covering with wet rug; covering with plastic sheets; and immersion in water, should be limited to the 28-day curing period. After 28 days curing period, the increase in compressive strength was not significant except for concrete cubes air-dried.

iii. Only concrete cured by immersion in lime and those covered with plastic sheet had their compressive strength meeting the minimum required 28 days strength (20 $N/mm^2$) for the particular mix used.

iv. The highest compressive strength was obtained for concrete cured by immersion in lime water, until after the 28-day curing period.

v. Generally, the least compressive strength was obtained for concrete cured by covering with wet rug. This result may be attributed to the outdoor (exposure) conditions that this curing method was subjected to.

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