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Effect of Delayed Water Curing on the Compressive Strength of Concrete with Different Water–Cement Ratios

Khalid Mousa [*1], Miftah Aybalu [2], Mohammed A. Ali [3], Aboubaker El-Qabja [4]
[1,2,3,4] Department of Civil Engineering, College of Engineering, Marj, University of Benghazi, Marj, Libya

تأثير تأخر المعالجة بالماء على مقاومة الضغط للخرسانة ذات نسب الماء إلى الأسمنت المختلفة

خالد موسى [*1]، مفتاح عيبلو [2]، محمد عادل علي [3]، أبوبكر القبجة [4]
[4،3،2،1] القسم الهندسة المدنية، كلية الهندسة المرج، جامعة بنغازي، المرج، ليبيا

[*]*Corresponding author:* Khalid.Mousa@uob.edu.ly

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Abstract:
Curing is a critical factor governing the development of concrete strength, as adequate moisture availability is necessary for continued cement hydration. However, delays in initiating water curing may occur under practical construction conditions and can adversely affect concrete strength development. This study experimentally investigates the effect of delayed water curing on the compressive strength of concrete with different water–cement ratios. Twelve concrete mixes were prepared using water–cement ratios of 0.50, 0.55, and 0.60, with water curing initiated immediately after casting or delayed by 12, 24, and 48 h. Compressive strength was evaluated at 7 and 28 days. The results showed a consistent reduction in compressive strength with increasing curing delay at all investigated water–cement ratios. After a 48 h delay, the reduction in 7-day compressive strength ranged from approximately 8.5% to 16.4%, while the corresponding reduction at 28 days ranged from approximately 10.2% to 20.6%, depending on the water–cement ratio. Increasing the water–cement ratio generally reduced compressive strength at both testing ages. However, the sensitivity to curing delay did not follow a simple trend with water–cement ratio, indicating that the magnitude of strength loss depended on both mixture proportion and curing delay. The findings emphasize the importance of initiating water curing as early as practicable, particularly under hot and dry environmental conditions.

Keywords: concrete; curing; delayed curing; compressive strength; water–cement ratio; water curing.

الملخص
تُعد المعالجة من العوامل الأساسية المؤثرة في تطور مقاومة الخرسانة، إذ إن توفر الرطوبة بصورة كافية يعد ضروريًا لاستمرار إماهة الأسمنت وتطور الخواص الميكانيكية للخرسانة. إلا أن تأخر بدء المعالجة بالماء قد يحدث في ظروف التنفيذ العملية، مما قد يؤثر سلبًا في تطور مقاومة الخرسانة. تهدف هذه الدراسة إلى تقييم تأثير تأخر المعالجة بالماء على مقاومة الضغط للخرسانة ذات نسب الماء إلى الأسمنت المختلفة. تم إعداد اثنتي عشرة خلطة خرسانية باستخدام نسب ماء إلى أسمنت مقدارها 0.50 و0.55 و0.60، مع بدء المعالجة بالماء مباشرة بعد الصب أو بعد تأخير قدره 12 و24 و48 ساعة. تم تقييم مقاومة الضغط عند عمرَي 7 و28 يومًا. أظهرت النتائج انخفاضًا منتظمًا في مقاومة الضغط مع زيادة مدة تأخر المعالجة لجميع نسب الماء إلى الأسمنت المدروسة. وبعد تأخير المعالجة لمدة 48 ساعة، تراوح الانخفاض في مقاومة الضغط عند عمر 7 أيام بين 8.5% و16.4%، بينما تراوح الانخفاض عند عمر 28 يومًا بين 10.2% و20.6%، وذلك باختلاف نسبة الماء إلى الأسمنت. كما أدى ارتفاع نسبة الماء إلى الأسمنت بصورة عامة إلى انخفاض مقاومة الضغط عند كلا العمرين. إلا أن حساسية الخرسانة لتأخر المعالجة لم تتبع اتجاهًا منتظمًا مع زيادة نسبة الماء إلى الأسمنت، مما يشير إلى أن مقدار فقدان المقاومة يعتمد على كل من نسب الخلط ومدة تأخر المعالجة. وتؤكد النتائج أهمية البدء في معالجة الخرسانة بالماء في أقرب وقت عملي ممكن، خاصة في الظروف البيئية الحارة والجافة.

الكلمات المفتاحية: الخرسانة، المعالجة، تأخر المعالجة، مقاومة الضغط، نسبة الماء الى الاسمنت، المعالجة المائية.

Introduction

Curing is one of the most important stages affecting concrete quality and the development of its mechanical properties. It provides suitable conditions for continued hydration between cement and water, thereby improving the microstructure of the cement paste and increasing the strength and durability of concrete. Previous studies have shown that inadequate or delayed curing can reduce compressive strength, increase permeability, and increase the likelihood of cracking and early-age shrinkage [3].

On construction sites, concrete may experience delays in the start of curing because of execution conditions, limited resources, or environmental factors. Such delays can adversely affect strength development, particularly during the first days after casting. This issue is especially important in hot and dry environments, where moisture loss during the first hours after casting can be relatively rapid.

Although numerous studies have investigated the influence of different curing methods on concrete properties, studies focusing specifically on delayed initiation of curing for defined short periods, together with different water–cement ratios, remain comparatively limited. James et al. [3] reported that curing method directly affects compressive strength, with water-immersed specimens achieving higher strength than specimens subjected to other curing conditions. The study also reported reductions in compressive strength and concrete density under inadequate curing.

Zakaria et al. [4] investigated different curing methods and water–cement ratios and found that increasing the water–cement ratio reduced compressive strength, while standard water curing produced the highest strength compared with air curing and other curing methods.

Talab and Marza [5] investigated delays in the start of curing of one, three, seven, and up to 28 days for normal- and high-strength concrete. Their results indicated that delayed curing reduced mechanical properties and durability, with the largest negative effect occurring when curing was delayed during the first day after casting. Microscopic observations also indicated lower hydration and increased porosity associated with delayed curing.

Garín et al. [6] confirmed that moisture conditions during curing have a significant influence on compressive strength and that differences in strength associated with curing conditions are also related to the water–cement ratio. White [7] further reported that early-age curing conditions and their duration are major factors affecting compressive strength at 28 days, and that deficiencies during the early stages are directly reflected in subsequent strength development.

Despite the number of studies addressing curing methods or water–cement ratio effects, research directly examining short delays of 12, 24, and 48 h at different water–cement ratios remains limited. Therefore, this study evaluates the combined effect of delayed curing initiation and water–cement ratio on the compressive strength of concrete at 7 and 28 days.

Materials and Methods

The study used commonly available materials for conventional concrete production. The materials were selected and subjected to the required laboratory tests to verify their suitability for the experimental program. The same sources of materials were used for all mixes to maintain consistency and minimize the influence of variables other than those investigated.

1 Cement

Ordinary Portland cement (OPC), type 42.5 N, produced in Beni Suef, Egypt, was used throughout the study. The same cement source was used in all concrete mixes so that differences in the measured results would primarily reflect the curing-delay and water–cement-ratio variables rather than changes in the binder. The cement was tested for its physical and mechanical properties, and the results are presented in Table 1.

Table 1. Physical and mechanical properties of the cement used

Test	Result	Standard
Cement fineness	8.57 %	ASTM C204
Initial setting time	120 min	ASTM C191
Final setting time	210 min	ASTM C191
Compressive strength at 3 days	23.03 MPa	ASTM C150
Compressive strength at 28 days	44.87 MPa	ASTM C150

2 Fine Aggregate

Clean natural sand sourced from Shatt Al-Badeen was used as the fine aggregate. Laboratory tests were conducted to determine its physical properties, cleanliness, and particle-size distribution in accordance with the relevant standards. Specific gravity and absorption were determined according to ASTM C128, the sand equivalent according to ASTM D2419, and sieve analysis according to ASTM C136. The results indicated that the sand had suitable cleanliness and grading for concrete production.

Table 2. Physical properties of the fine aggregate

Test	Result	Standard
Specific gravity	2.711	ASTM C128
Water absorption	0.79 %	ASTM C128
Sand equivalent	76.8 %	ASTM D2419
Fineness modulus	—	ASTM C136

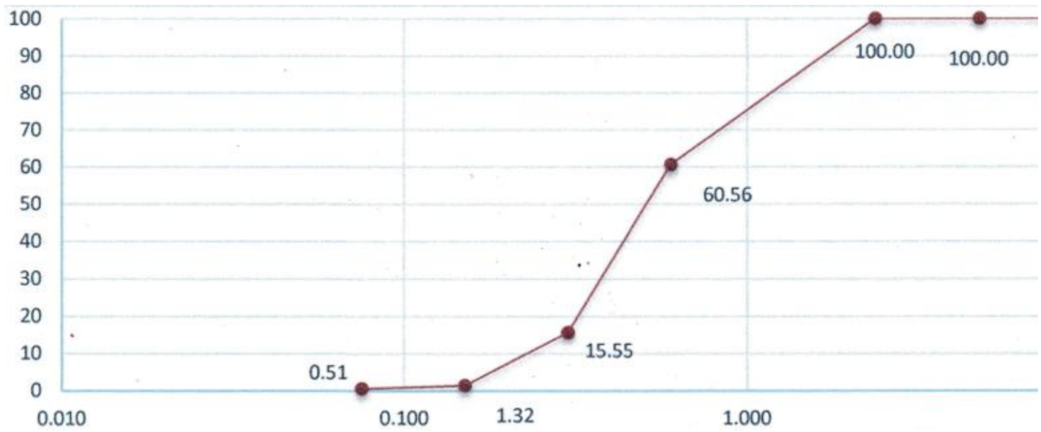

Figure 1. Particle-size distribution curve of the fine aggregate.

3 Coarse Aggregate

Natural coarse aggregate obtained from a quarry in the Al-Jihashiya area near Al-Abyar was used in two nominal size ranges, 10–20 mm and 5–10 mm, to improve grading and packing of the concrete mixture and reduce internal voids. The coarse aggregate was evaluated through tests for aggregate crushing value, aggregate impact value, Los Angeles abrasion, magnesium sulfate soundness, specific gravity, absorption, material passing the No. 200 sieve, flakiness index, chloride content, sulfate content, and sieve analysis.

Table 3. Physical and mechanical properties of the coarse aggregate

Test	Result " 10–20 mm "	Result "5-10 mm"	Standard
Los Angeles abrasion	27.41 %	29.50 %	ASTM C131 / C535
Magnesium sulfate soundness	3.87 %	5.47 %	ASTM C88
Specific gravity	2.535	2.528	ASTM C127
Water absorption	1.63 %	1.95 %	ASTM C127
Material passing No. 200 sieve	0.92 %	1.01 %	ASTM C117
Flakiness index	10.24 %	16.19 %	BS 812-105.1
Chloride content (Cl)	0.00221 %	0.00287 %	BS 1377: Part 3
Sulfate content (SO_4)	0.00715 %	0.00813 %	BS 1377: Part 3

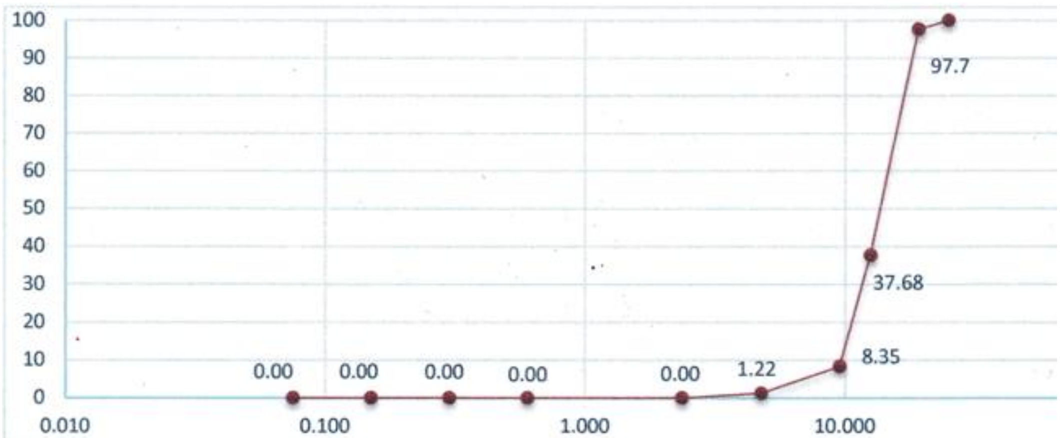

Figure 2. Particle-size distribution curve of the 10–20 mm coarse aggregate.

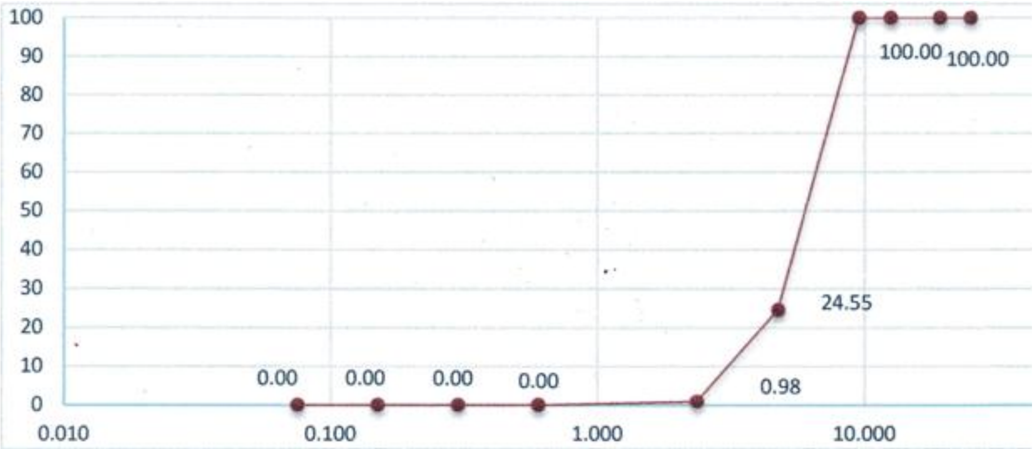

Figure 3. Particle-size distribution curve of the 5–10 mm coarse aggregate.

The results showed that both coarse aggregate size ranges had suitable strength and hardness and low levels of undesirable materials, making them suitable for the concrete mixtures investigated.

4 Mixing Water

Potable water free from harmful impurities, oils, and salts was used for all concrete mixes. The use of potable water was intended to avoid adverse effects on setting time, compressive strength, and durability and to satisfy the general requirements for concrete mixing water.

5 Concrete Mix Design

Mix Proportions

A constant nominal mix proportion of 1:2:4 was adopted for all concrete mixes, while only the water–cement ratio was varied to investigate its influence on concrete sensitivity to delayed curing. Three water–cement ratios were used: 0.50, 0.55, and 0.60. The twelve mixes are summarized in Table 4.

Table 4. Details of the concrete mixes

Mix	w/c	Curing delay
1	0.50	0 h
2	0.50	12 h
3	0.50	24 h
4	0.50	48 h
5	0.55	0 h
6	0.55	12 h
7	0.55	24 h
8	0.55	48 h
9	0.60	0 h
10	0.60	12 h
11	0.60	24 h
12	0.60	48 h

Specimen Preparation and Curing

Immediately after mixing, the slump test was conducted to evaluate the workability of the fresh concrete in accordance with BS 1881 Part 102. Twelve concrete mixes were prepared, with each set of four mixes representing a constant water–cement ratio. Six standard 150 × 150 × 150 mm concrete cubes were cast for each mix, giving a total of 72 specimens. Three cubes from each mix were tested for compressive strength at 7 days, while the remaining three cubes were tested at 28 days.

After casting, the specimens assigned to the reference condition were subjected to water curing as soon as practicable, whereas the specimens assigned to delayed-curing conditions were kept during the designated delay period under laboratory ambient conditions, at room temperature and normal ambient relative humidity. The curing delays were 12, 24, and 48 h. After completion of the assigned delay period, the specimens were transferred to the standard water-curing conditions and remained under curing until the designated testing age of 7 or 28 days.

All specimens were subjected to the same curing procedure after the specified delay period so that the primary experimental variables were the duration of curing delay and the water–cement ratio. The curing environment and handling procedures were kept consistent for all mixtures to minimize the influence of uncontrolled experimental variables.

Results and Discussion

1 Slump Test

The slump test was conducted immediately after mixing for all concrete mixes to evaluate the workability of the fresh concrete.

Figure 4. Slump test of the fresh concrete

Table 5. slump test

no	w/c	slump
1	**0.50**	**3 cm**
2	**0.55**	**5 cm**
3	**0.60**	**9 cm**

2 Compressive Strength Test

The compressive strength results obtained at 7 and 28 days are presented in Table 6. The results demonstrate the influence of both curing delay and water–cement ratio on the measured compressive strength.

Table 6. Compressive strength results at 7 and 28 days

Mix	w/c	Curing delay	7-day strength (MPa)	28-day strength (MPa)
1	0.50	0 h	31.33	39.02
2	0.50	12 h	30.27	37.05
3	0.50	24 h	29.39	33.70
4	0.50	48 h	28.67	30.97
5	0.55	0 h	27.60	33.78
6	0.55	12 h	26.03	32.13
7	0.55	24 h	25.32	31.85
8	0.55	48 h	25.01	30.32
9	0.60	0 h	26.33	31.88
10	0.60	12 h	25.68	30.05
11	0.60	24 h	25.49	29.44
12	0.60	48 h	22.02	27.32

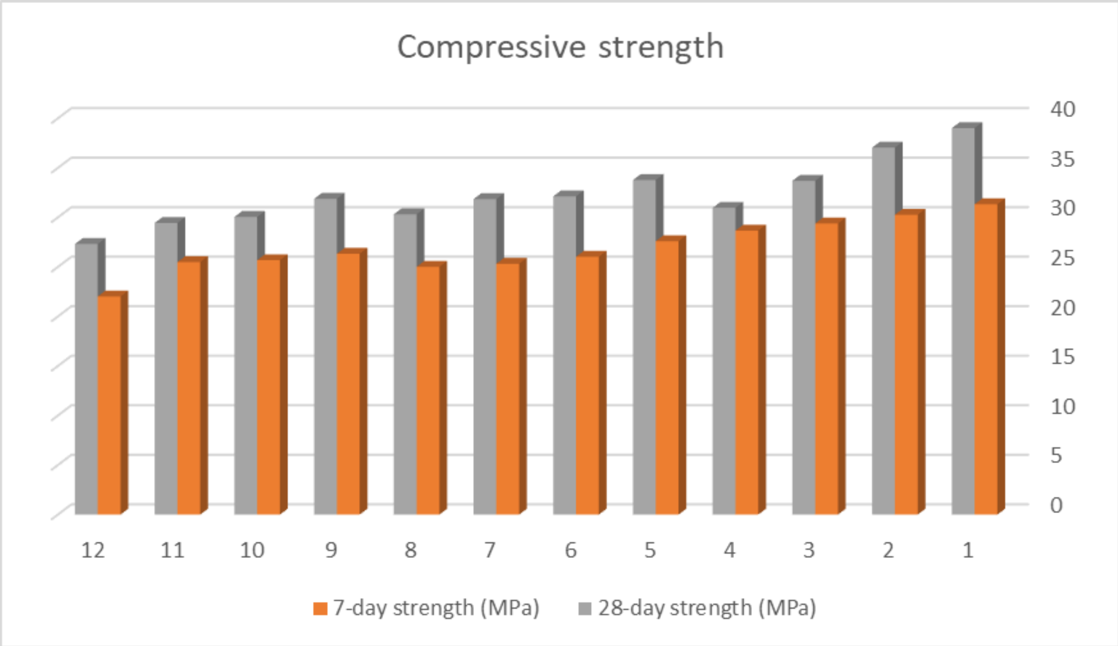

Figure 5. Compressive strength results at 7 and 28 days

Effect of Curing Delay on 7-Day Compressive Strength

The 7-day compressive strength decreased progressively with increasing curing delay for all three water–cement ratios. For w/c = 0.50, the strength decreased from the immediately cured condition to the 48 h delayed condition, while similar reductions were observed for w/c = 0.55 and 0.60. The reduction indicates that the first hours after casting are important for early strength development.

This behavior can be attributed primarily to the availability of moisture during the early hydration period. When water curing is delayed, moisture can be lost from the concrete surface, reducing the amount of water available for continued cement hydration. This limits the formation and development of hydration products and can result in a less dense cementitious matrix. Consequently, the concrete develops lower compressive strength at the early testing age.

The magnitude of the reduction was not identical for the three water–cement ratios. After a 48 h curing delay, the relative reduction in 7-day strength was approximately **8.5% for w/c = 0.50, 9.4% for w/c = 0.55, and 16.4% for w/c = 0.60**. The larger reduction observed for w/c = 0.60 may be associated with its higher water content and the greater potential for capillary pore development after hardening. However, because only three water–cement ratios were investigated, this observation should be interpreted as an experimental trend rather than a universal relationship.

Effect of Curing Delay on 28-Day Compressive Strength

The adverse effect of delayed curing was also evident at 28 days. For all three water–cement ratios, the specimens subjected to longer curing delays developed lower compressive strength than the corresponding immediately cured specimens. This indicates that the effect of inadequate moisture availability during the early period was not completely eliminated by subsequent water curing.

The persistence of the strength reduction can be explained by the fact that hydration and microstructural development during the early stages establish the subsequent development of the cementitious matrix. Although subsequent water curing allows hydration to continue and may partially compensate for the initial deficiency, it cannot necessarily restore the microstructure to the same condition that would have developed under continuous early curing.

The 48 h delay produced reductions of approximately **20.6%, 10.2%, and 14.3%** in 28-day compressive strength for w/c ratios of 0.50, 0.55, and 0.60, respectively. Interestingly, the largest reduction at 28 days occurred at w/c = 0.50 rather than at the highest water–cement ratio. Therefore, the present results do not support the assumption that increasing the water–cement ratio necessarily increases sensitivity to curing delay at all testing ages.

Effect of Water–Cement Ratio

The results demonstrate that increasing the water–cement ratio generally reduced compressive strength at both 7 and 28 days. The mixtures with w/c = 0.50 generally achieved the highest strength, whereas those with w/c = 0.60 generally recorded the lowest strength.

The reduction in strength with increasing water–cement ratio can be explained by the higher amount of water available relative to cement. After hardening, the water that is not consumed during hydration can contribute to the formation of capillary pores. A higher volume and connectivity of capillary pores can reduce the density and load-carrying capacity of the hardened cement paste, thereby reducing compressive strength.

The influence of curing delay, however, was not directly proportional to the water–cement ratio. At 7 days, the largest percentage reduction after 48 h was observed for w/c = 0.60, whereas at 28 days the largest reduction occurred for w/c = 0.50. This variation indicates that curing delay and water–cement ratio interacts in a more complex manner than a simple linear relationship. The observed behavior may also be influenced by the relatively limited number of water–cement ratios and specimens investigated in the present study.

General Discussion

The overall experimental results demonstrate that the timing of water curing is an important factor in concrete strength development. Increasing the curing delay from immediate curing to 48 h resulted in lower compressive strength at both 7 and 28 days for all investigated water–cement ratios. This consistent trend indicates that the moisture condition during the early period after casting has a lasting influence on the development of the cementitious microstructure.

The underlying mechanism is mainly related to cement hydration and moisture availability. Cement hydration requires water, and maintaining adequate moisture during the early stages promotes the formation of hydration products and the progressive densification of the cement paste. When curing is delayed, moisture loss may interrupt or slow these processes, leading to a less developed and potentially more porous internal structure. Subsequent curing can promote additional hydration, but the strength results indicate that the effect of the initial delay was not completely eliminated by later water curing.

The influence of the water–cement ratio provides an additional explanation for the observed differences among the mixtures. Increasing the water–cement ratio generally reduced compressive strength because of the greater potential for capillary pore formation. Nevertheless, the relative effect of curing delay varied with both the water–cement ratio and testing age. This indicates that the effect of curing cannot be evaluated independently from mixture proportions.

From a practical perspective, these findings emphasize that water curing should begin as soon as practicable after the completion of casting and finishing operations. This is particularly important when concrete is exposed to conditions that can accelerate moisture loss. However, the present laboratory study was conducted under controlled experimental conditions, and therefore the magnitude of the observed reductions should not be directly generalized to specific field environments without considering actual temperature, relative humidity, wind, solar exposure, and concrete surface conditions.

Conclusion

This experimental study investigated the effect of delaying the initiation of water curing by 12, 24, and 48 h on the compressive strength of concrete with water–cement ratios of 0.50, 0.55, and 0.60. Based on the experimental results, the following conclusions can be drawn:

- Delaying the initiation of water curing generally reduced the compressive strength at both 7 and 28 days, with the reduction becoming more evident as the curing delay increased.
- Increasing the water–cement ratio generally reduced the compressive strength of concrete. The mixtures with w/c = 0.50 generally achieved the highest strength, whereas those with w/c = 0.60 generally recorded the lowest strength.
- The magnitude of the strength reduction caused by curing delay varied with both the water–cement ratio and testing age. Therefore, the present results do not support a simple relationship in which higher water–cement ratios always produce greater sensitivity to curing delay.
- At 28 days, the effect of curing delay remained significant. For example, at w/c = 0.50, the compressive strength decreased from 39.02 MPa for immediate curing to 30.97 MPa after a 48 h delay.
- The results highlight the practical importance of initiating water curing as early as practicable after casting and finishing, particularly under hot and dry environmental conditions where moisture loss may be rapid.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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