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An Evaluation of Sustainable Brick Powder as a Partial Cement Replacement in Reactive Powder Concrete: Influence of Curing Techniques on Strength Development

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ABSTRACT

This study aims to investigate the effect of different curing methods on the strength of reactive powder concrete (RPC) and to evaluate the use of brick powder as a partial replacement of cement. The use of brick powder is intended to reduce cement content and utilize construction waste more sustainably. In this work, waste clay bricks collected from construction sites were crushed into fine powder and used at replacement levels of 5% and 10%. The mixtures were subjected to different curing methods, including standard curing (C.S), coating curing, and warm water curing, followed by standard curing. The warm curing included immersion in water at (35 ± 2) °C for one day (W1S), two days (W2S), and three days (W3S), followed by standard curing until testing. The results showed that the compressive strength of the control mix under standard curing reached 92.5 MPa at 28 days. The strength increased by 11.24%, 21.72%, 25.08%, and 29.83% for (C.S), (W1S), (W2S), and W3S, respectively .In addition, the mixture with 10% brick powder showed better performance, with increases of 30.94%, 31.89%, and 32.77% in compressive strength, 29.03%, 29.60%, and 30.50% in flexural strength, and 27.80%, 28.89%, and 29.99% in tensile strength at 7, 28, and 90 days, respectively, compared to the control mix. Overall, the results suggest that brick powder can be used as a sustainable material in RPC, especially when combined with suitable curing methods.

Keywords: Brick powder, Coating curing, Reactive powder concrete, Sustainable concrete, Warm-standard curing.

1. INTRODUCTION

Reactive Powder Concrete (RPC) is a promising ultra-high-performance cementitious composite because of its well-known strength and durability **(Altamiranda-Ramos et al., 2025)**. The mixture consists of cement, silica fume, and ultra-fine sand, carefully formulated to enhance the microstructure of each component, thereby achieving the highest possible

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density **(Khitab et al., 2022)**. Through increasing compressive strength, bridging microcracks to improve tensile and flexural capacity, and ensuring more uniform fiber distribution, short steel fibers greatly enhance the mechanical performance of RPC, reducing brittleness and improving overall durability **(Ni et al., 2024)**. However, the production of cement and concrete contributes about 5–8% of global CO_2 emissions due to the high energy requirements of clinker production and limestone processing. Therefore, sustainable approaches such as using supplementary cementitious materials and alternative binders have been widely investigated to reduce the environmental impact of concrete production **(Miller et al., 2024)**. Waste from construction and demolition activities can be processed into fine powder and reused in cement-based materials as a partial replacement for cement, contributing to more sustainable construction practices **(Kaptan et al., 2024)**.

The use of pozzolanic materials plays an important role in enhancing the properties of concrete. The pozzolanic reaction improves strength development and leads to a denser microstructure of the cement paste **(Ahmad, 2022; Shannag and Yeginobali, 1995; Shannag, 2000)**. This improvement is mainly related to the fineness of particles, which increases their reactivity with calcium hydroxide [$Ca(OH)_2$], resulting in the formation of additional cementitious compounds. In this context, brick powder has gained attention as a potential pozzolanic material due to its chemical composition and availability.

Previous studies have shown that brick powder can influence the mechanical and rheological properties of concrete. Some studies reported that the addition of recycled brick powder may increase water demand and affect workability **(Kryzhanovskyi et al., 2025**), while others observed that its use as a partial cement replacement can improve compressive strength at certain replacement levels. For example, a 10% replacement level showed the highest increase in compressive strength after 28 days compared to the control mix. These findings highlight the potential of brick powder as a sustainable material in concrete production. During the firing process, bricks undergo chemical transformations that result in the formation of amorphous silica-aluminate phases, which contribute to their pozzolanic activity **(Chen et al., 2023; Wu et al., 2023; Kırgız, 2016)**. However, the effectiveness of brick powder depends on several factors, including particle size and replacement ratio. While it can act as a micro-filler and improve long-term properties, it may also lead to reduced early-age strength and limitations in the allowable replacement percentage **(Ouyang et al., 2021)**. Several studies have investigated the use of brick powder as a partial cement replacement **(Naceri and Hamina, 2009; Ge et al., 2015; He et al., 2021)**. Based on the above, previous studies indicate that the use of brick powder as a partial replacement of cement can affect the mechanical properties of concrete depending on the replacement level and curing conditions.

This work builds upon previous studies by the authors, while introducing a new combined approach involving curing cycles and brick powder replacement in RPC. Therefore, this study aims to investigate the combined effect of warm water curing cycles (1, 2, and 3 days at 35°C) and partial replacement of cement with brick powder on the mechanical performance of reactive powder concrete (RPC). Unlike previous studies, which have typically examined either curing conditions or material replacement independently, this study focuses on their combined influence, providing a more comprehensive understanding of their interaction.

2. EXPERIMENTAL PROGRAM

The experimental procedures conducted in this study are outlined in **Fig. 1.**

2.1 Ingredients-Materials

- Ordinary Portland Cement (OPC): Conforming to **(IQS No. 5, 2019),** which is comparable to **(ASTM C150/C150M, 2024),** as specified in **Tables 1** and **2**
- Fine Sand (Sika, finer than 0.6): Meeting the requirements, as outlined in **Table 3**.
- Superplasticizer (SP): SikaViscocrete-180GS, Type F&G, compliant with **(ASTM C494, 2024).**
- Silica Fume (SF): Amorphous sub-micron powder S-F with a strength activity index of 111%, in accordance with **(ASTM C1240, 2015)**, as detailed in **Table 4**.
- Micro Steel Fiber (MSF): Straight steel fibers with a nominal diameter of 0.2 mm and a length of 13 mm, resulting in an aspect ratio (L/D) of 65.
- Water (W): Tap water that complies with Iraqi Specification **(IQS No. 1703,2018)**.
- Broken Clay Brick: Used as a partial cement replacement at 5% and 10%, after being converted to powder, in accordance with **(ASTM C618, 2018),** as detailed in **Table 5** and **Fig. 2**. A particle size distribution test was conducted using Brookhaven Instruments Corp.'s 90Plus Particle Sizing System, as illustrated in **Fig. 3**.

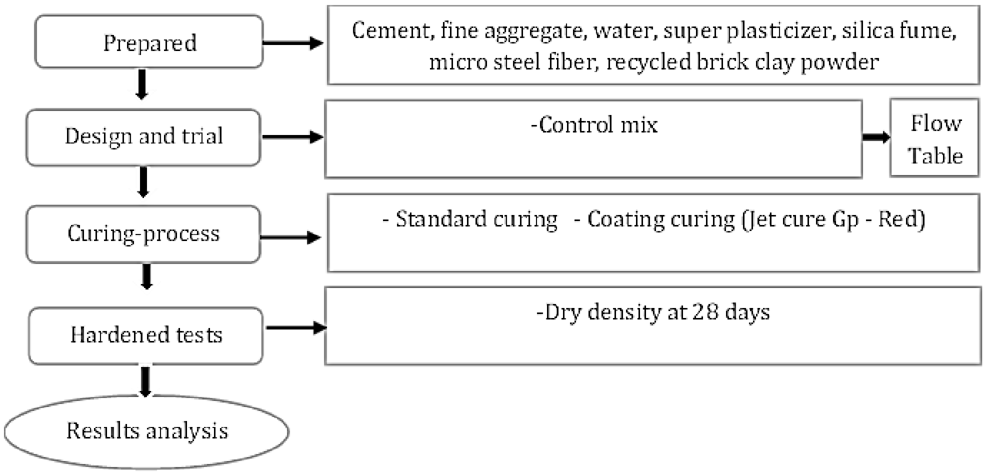


Figure 1. Experimental program

Table 1. Cement physical properties

Propriety		Results	Limits of (IQS No. 5, 2019)
Specific-surface area (m²/kg)		387	≥ 280
Soundness by Autoclave (%)		0.68	0.80≤
Initial Vicat's Setting time(min)		147	≥45
Final Vicat's Setting time(min)		329	≤600
Compressive-Strength	2-days (MPa)	28	≥20-R
	28-days (MPa)	47	≥42.5

Table 2. Cement chemical properties

Compositions oxide	Results weight (%)	Limits of (IQS No. 5, 2019)
(IR)	0.51	≤ 1.5 %
(MgO)	3.26	≤ 5 %
(LOI)	2.53	≤ 4 %
(SO_3)	2.42	SO_3≤ 2.8
Calculation of Bogue equations in accordance with **(ASTM C150, 2024)**		
(C_3A)	8.26	-

Table 3. Requirements of sand.

Physical & Chemical Characteristics	Result	Limit of (IQS No.45, 2019)
Specific gravity	2.5	-
Absorption (%)	1.3	-
(SO_3) (%)	0.00	≤ 0.50

Table 4. Chemical requirements of silica fume

Composition oxide (%)	Results (%)	Limits of (ASTM C1240, 2020)
(SiO_2)	92.2	≥ 85
(MgO)	0.62	-
(AL_2O_3)	1.5	-
(Fe_2O_3)	1.3	-
(CaO)	0.55	-

Table 5. Properties of powder-clay brick waste.

Properties		Results	Limits of (ASTM C618, 2018)
Physica	**Retained wet sieved 45 µm (%)**	12	≤ 34
	Index Strength activity (%)	85	≥75 at 7 days
	Specific gravity	2.25	-
Chemical	**SiO_2 (%)**	70.8	Sum ≥70
	Al_2O_3 (%)	11.3	
	$F_{e2}O_3$ (%)	3.2	
	SO_3 (%)	0. 10	≤ 4
	LOI (%)	2.2	≤ 10

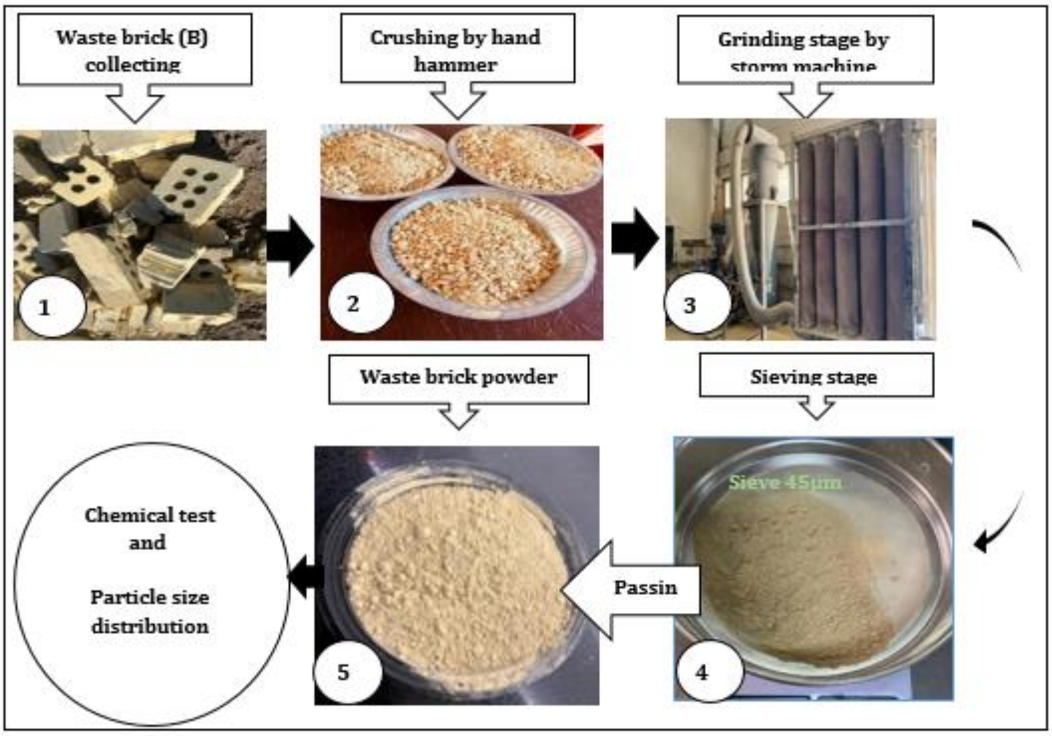


Figure 2. Stages of collection and preparation of crushed brick powder.

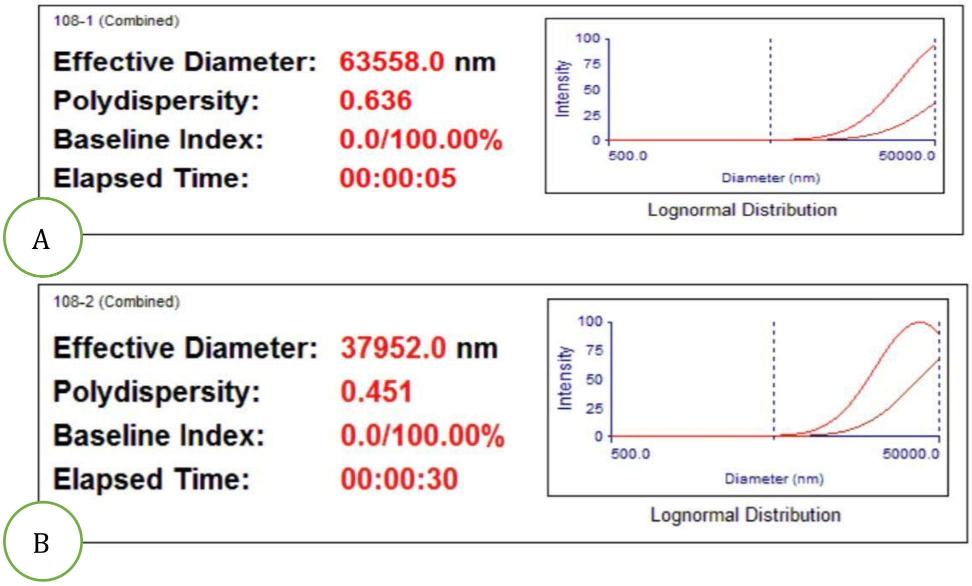


Figure 3. Particle size distribution test of (A) clay brick powder, (B) cement.

2.2 Design and Preparation

2.2.1 Design and Mixes

The RPC production according to the author-lines established by **(Richard and Cheyrezy, 1995)**, alongside other trial mixtures. This research included the design of two types of mixtures: a control mixture comprising 100% cement, and a sustainable (B5 and B10) mixture including recycled brick clay as a partial cement substitute at ratios of 5% and 10% by weight. The water-to-cement ratio was consistently maintained at 0.227 in all mixtures. **Table 6** provides a detailed breakdown of the components of the selected materials. The flow table results for all mixtures were consistent with **(ASTM C1437, 2020)**, which specifies a target value of 110 ± 5 mm. The recorded flow values were 110 mm for the control mixture, 113.5 mm for 5% replacement, and 112 mm for 10% replacement. **Fig. 4** displays the flow table process.

Table 6. Mixture contents, kg/m^3

Mix ID	Cement	Clay Brick powder
Control mixture	900	0
B5%	855	45
B10%	810	90
Constant content: sand=1200; W=250; silica fume=200; Steel Fiber=156; SP=17.6 L/m^3		

2.2.2 Mixing and Casting

This investigation's mixing program, with the procedures shown in **Fig. 5**, was derived from the works of **(Richard and Cheyrezy, 1995)**. Cubes (100x100x100 mm), cylinders (100x200 mm), and prisms (50x50x250 mm) were the three mold shapes that were produced. A vibration table was used to consolidate all of the molds. According to **(ASTM C192, 2019)**, cubic molds were filled in two layers; cylindrical molds were filled in one layer; and prismatic molds were filled in two layers per **(BS EN 12390-2, 2019)**.

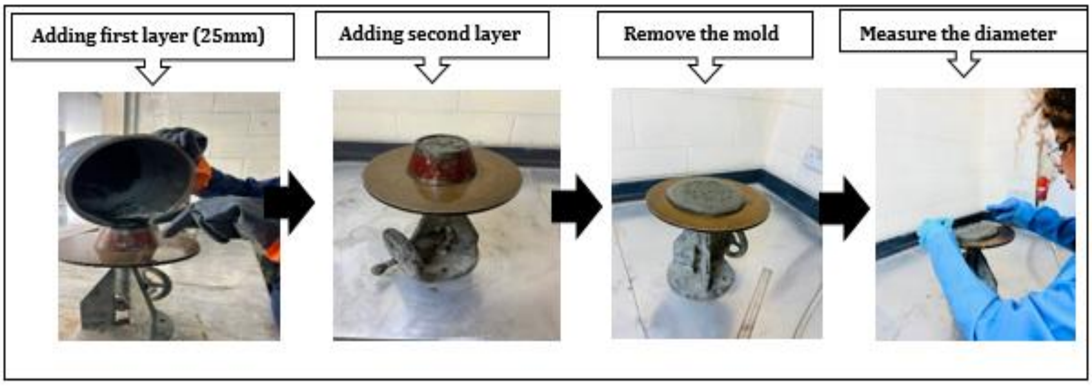


Figure 4. Flow table test procedure

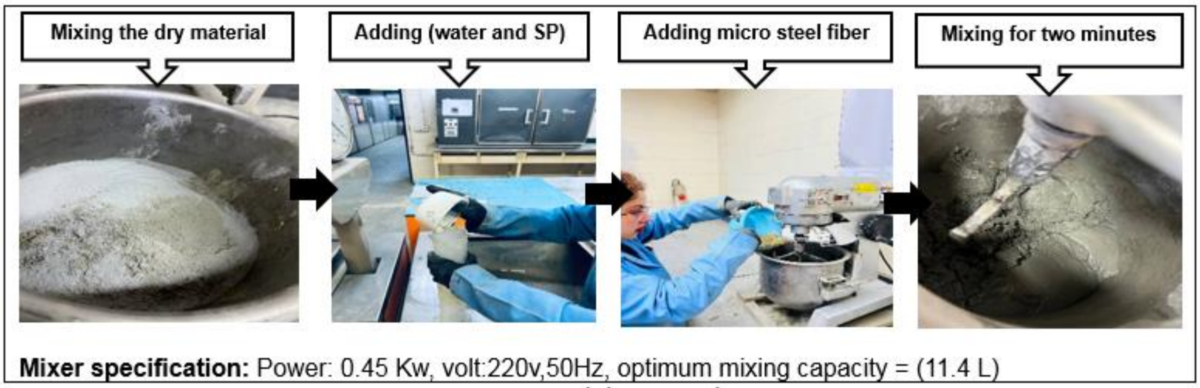


Figure 5. Mixing procedure

2.2.3 Curing and Testing

The effect of different curing procedures on RPC mechanical strength was compared to that of standard curing in this study, as presented in **Fig.6,** which displays the curing procedures, and **Fig.7** displays the curing cycle for one day. It should be noted that **Fig.7** represents a single curing cycle (24 hours). The curing regimes W1S, W2S, and W3S correspond to 1, 2, and 3 days of curing in 35°C water, respectively, where the same cycle is repeated once per day, followed by standard curing.

Standard curing (S): In compliance with **(ASTM C192, 2019)**, the specimens were immersed in room temperature normal water.

Warm + standard curing (WS): Specimens were initially immersed in water at (35 ± 2) °C, followed by immersion in standard water, for a specific duration. The curing conditions were as follows: W1S: 1 day in 35°C water + 27 days of standard curing; W2S: 2 days in 35°C water + 26 days of standard curing; W3S: 3 days in 35°C water + 25 days of standard curing.

Coating (C): Specimens were coated with Jet cure (GP red) after casting.

The mechanical strength tests (compressive, flexural, and splitting tensile strengths) were performed. **Table 7** delineates the specifics of these tests. And the physical properties of the concrete were evaluated by performing tests on fresh **(ASTM C138, 2017)** and dry density **(Iraqi guidelines 274, 2000)**.

Table 7. The mechanical characteristics of samples*

strength Test and specification	Compressive **(BS EN 12390-2, 2019)** $fc = \frac{P}{A}$	Tensile **(ASTM C496, 2017)** $ft = \frac{2P}{\pi lD}$	Flexural **(ASTM C293, 2016)** $fr = \frac{3PL}{2bd^2}$
Specimen dimensions and compaction	-Cube (10) cm -Two layers	Cylinder (10*20) cm -One layer	Prism (5x5x25) cm -Two layers
Photo-tests			

* Applicable for 7, 28, and 90 days

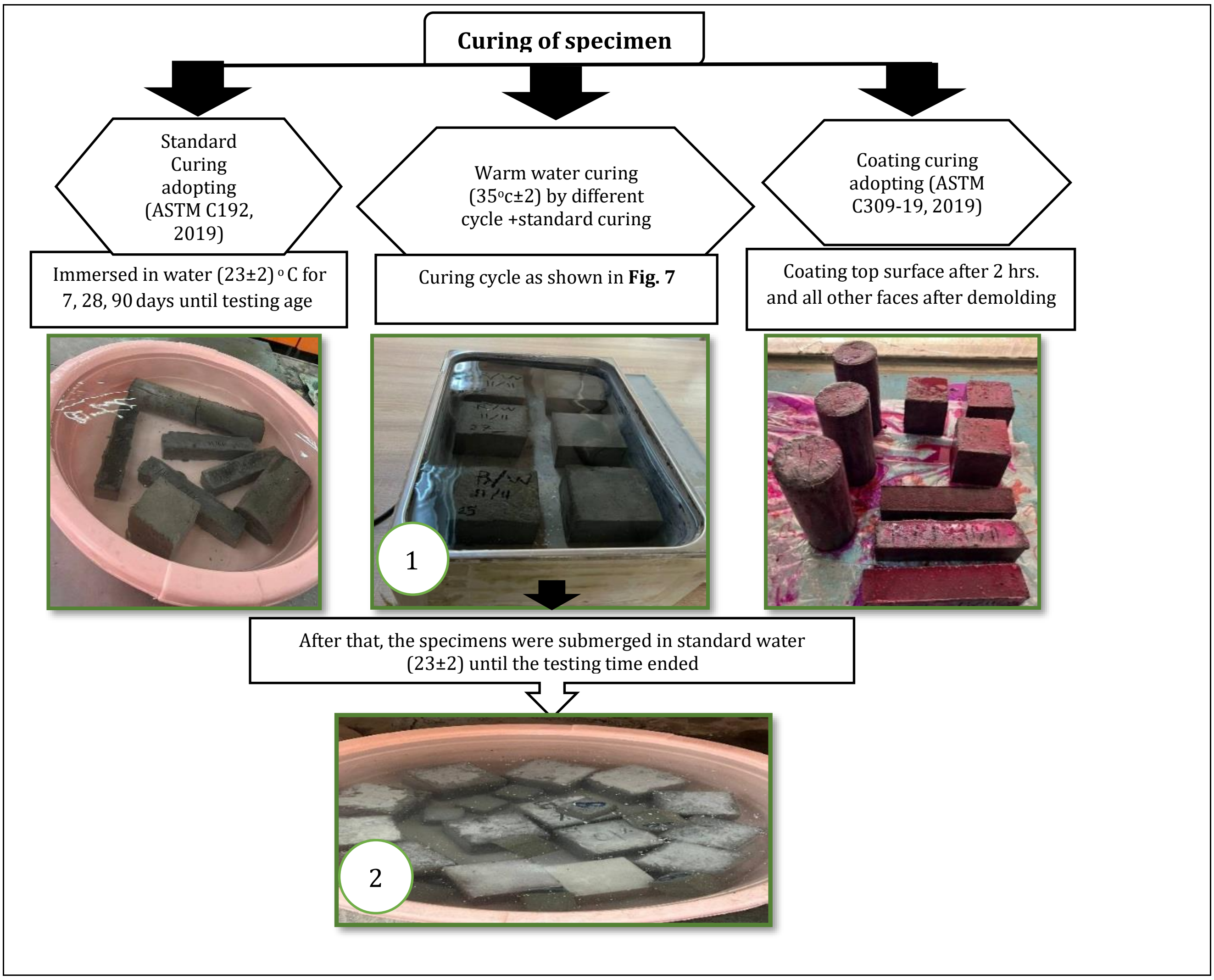
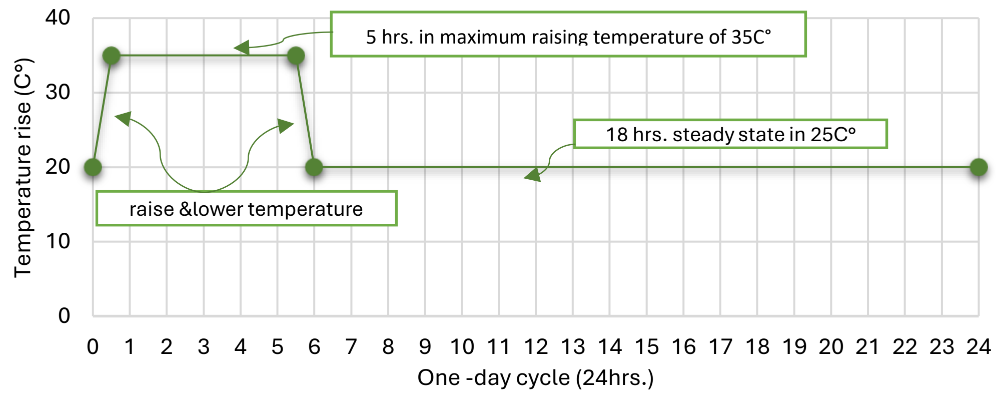


Figure 6. Curing of specimens



Time in lab (hr.: min)	Details information by hours
8:00 am.	Turn on accelerated curing bath from 25C° after extracting specimens from molds
8:30 am.	The accelerated path reaches the 35C° during 30min
8:30 am. to 1:30pm.	5 hrs. in maximum raising temperature of 35C°
1:30pm.	Turn of accelerated curing bath
2:00 pm.	≈ return to 25C°
2:00 pm. to 8:00 am.	18 hrs. steady state in 25C° (finish one day cycle)

Figure 7. Curing cycle (one day)

3. RESULTS AND DISCUSSION

3.1 Dry and Fresh Density Tests

The fresh density of control mixture (RPC) and sustainable RPC equal to 2724±5 kg/m^3, the convergent density referred to the cement weight replacement by prepared powder brick maintain the fresh density approximately the same as presented in **Fig. 8**. Although the 28-days-dry-density of control mixture equal to 2785kg/m^3, the percentage improvement of dry-fresh density of B5-N (5% brick powder replacement under standard curing) and B10-N (10% brick powder replacement under standard curing) was equal to (8.14 and 8.77) % respectively which presents the good development of pozzolana- cement hydration reactions. This agrees with **(Letelier et al., 2018)**, which found that brick substitution in concrete increased hardened density.

3.2 Strength- Lab Tests Evaluation

For standard curing conditions, the results of the control-standard curing mixture (C.S) mixture compressive strength equal to 74.2 MPa, 92.5 MPa, and 100.6 MPa after 7,28 and 90 days, respectively, as presented in **Table 8**. The improvement of C.C, C.W1S, C.W2S, and C.W3S compared to standard curing exposure (C.S) 28 days ≈ (11.24%, 21.72%, 25.08%, and 29.83%) respectively as shown in **Fig. 9**. The optimal enhancement achieved by application of C.W3S for all-ages due to the positive effects of three days-cycle of simple and executable local technique provide a good heating warm water environment for specimens, suitable to cement ingredients hydrated, which can be analogical results with **(Hendi and Aljalawi, 2024; Hiremath and Yaragal, 2017)**. Although the coated way compressive strength developments reading was the lowest, the restriction of evaporation can be significant and a visual sign of microcracking healing can be observed.

Sustainable mixtures (B5.S and B10.S) for standard curing exhibit compatibility-mode enhancement effects exposed to different curing systems, as shown in **Fig. 10**, which means that the replacement of cement by pozzolanic brick powder exhibits an analogous trend in development strength with an acceptably higher variance due to the combined effects of curing and brick powder variance. The essential production of (C-S-H) gel due to the reaction of calcium hydroxide from silicates hydration (C_3S and C_2S) of cement and the active silica from pozzolana-brick waste powder, led to densification density reducing air voids with strength improvement **(Hu et al., 2024; Kryzhanovskyi et al., 2025; Rahhal et al., 2019; Zhang et al.,2024)**. **Fig. 11** presents compressive strength improvements that comply with **(Serkan and Altan, 2024; Tawfik et al., 2024)**.
Fig. 12 for splitting-tensile and flexure strength for (C.S) mixture, in addition to **Figs. 13 and 14** for tensile and flexural strength, respectively, for both mixtures (B5 and B10), which presents the effects of different external curing compared to the standard curing process. The percentage improved for all R.P.C specimens with the same trend-mode for compressive, referred to harmonies and homogeneity results, which is explained as cement hydration due to the curing type. Finally, **Figs. 15** and **16** show the framework effects of brick powder on flexural and tensile strengths, which were similar to compressive. The cement- natural pozzolana reaction is more significant with later age, according to surface texture behavior, activating capacity of micro brick powder, and intra-zone intrafraction between paste and fine aggregate.

Table 8. Strength lab test results.

Mixture ID	Compressive strength (MPa)			Tensile strength (MPa)			Flexural strength (MPa)		
	7 days	28 days	90 days	7 days	28 days	90 days	7 days	28 days	90 days
C.S	74.2	92.5	100.6	6.625	8.228	9.015	7.645	9.552	10.508
C.C	82.0	102.9	113.2	7.122	8.952	9.871	8.272	10.459	11.580
C.W1S	88.8	112.6	122.5	7.791	9.717	10.710	9.059	11.482	12.694
C.W2S	92.5	115.7	125.8	8.116	10.162	11.161	9.419	11.797	13.040
C.W3S	94.5	120.1	130.7	8.268	10.301	11.431	9.640	12.112	13.398
B5.S	80.2	101.0	111.1	6.980	8.860	9.920	8.137	10.299	11.492
B5.C	89.0	113.1	125.6	7.524	9.666	10.882	8.844	11.333	12.744
B5.W1S	96.7	123.8	137.0	8.229	10.526	11.854	9.736	12.510	14.051
B5.W2S	101.0	127.4	140.8	8.627	11.048	12.410	10.171	12.907	14.504
B5.W3S	103.4	132.4	146.6	8.858	11.323	12.757	10.452	13.309	14.971
B10.S	80.8	101.9	112.3	7.060	8.980	10.080	8.200	10.387	11.609
B10.C	90.7	114.2	128.1	7.639	9.842	11.098	8.930	11.444	12.879
B10.W1S	98.7	125.0	139.1	8.359	10.731	12.106	9.842	12.636	14.205
B10.W2S	102.9	129.3	143.2	8.769	11.279	12.711	10.284	13.050	14.677
B10.W3S	105.8	134.4	149.1	9.023	11.575	13.104	10.581	13.462	15.150

Note: C refers to the control mixture, while B5 and B10 refer to mixtures containing 5% and 10% brick powder, respectively. S indicates standard curing, C indicates coating curing, and W1S, W2S, and W3S indicate warm water curing for 1, 2, and 3 days, followed by standard curing.

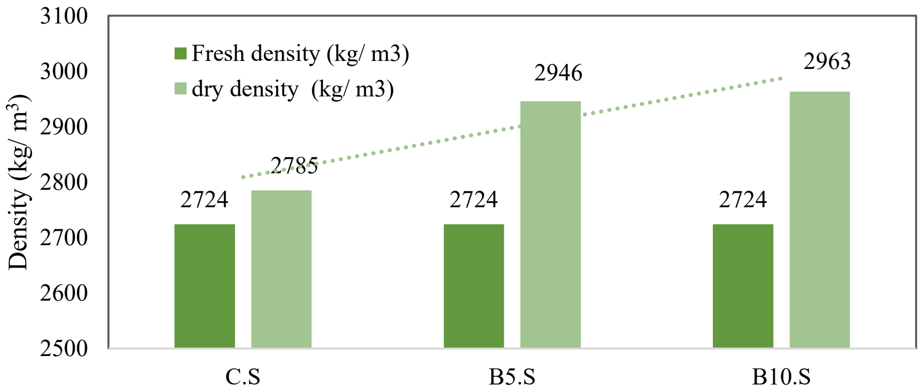


Figure 8. Density of the R.P.C mixtures

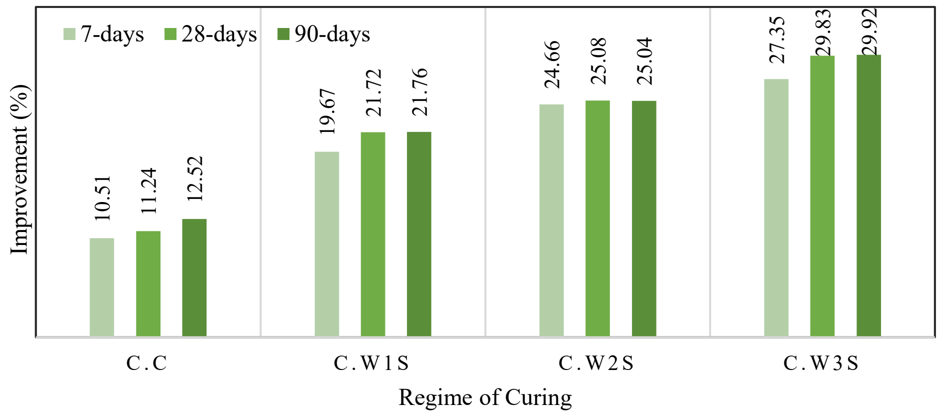


Figure 9. Comparison of the different curing systems with standard curing (C.S) for the control mixture in compressive strength

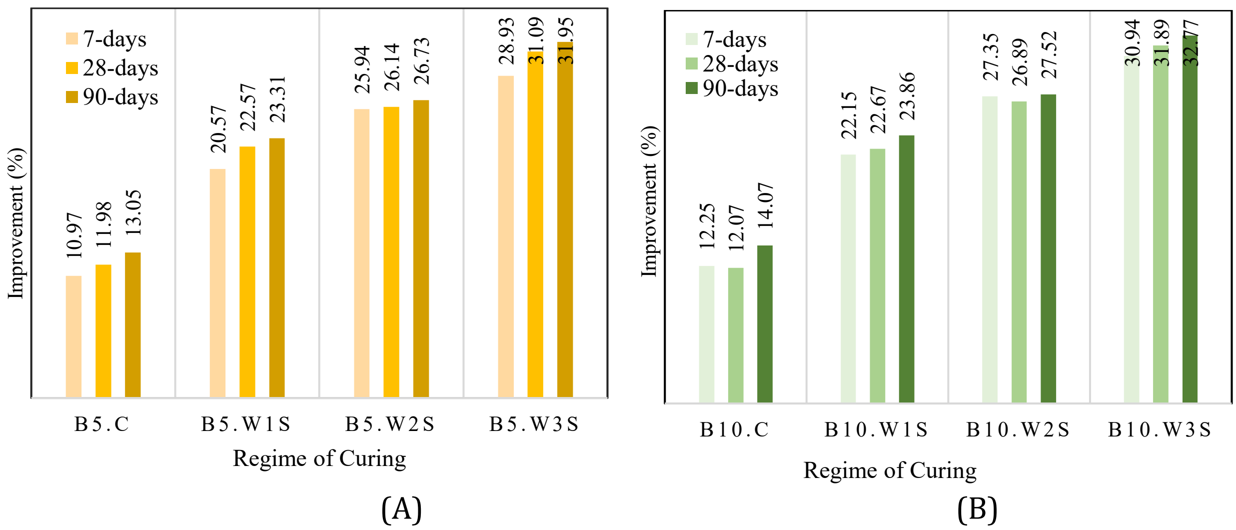
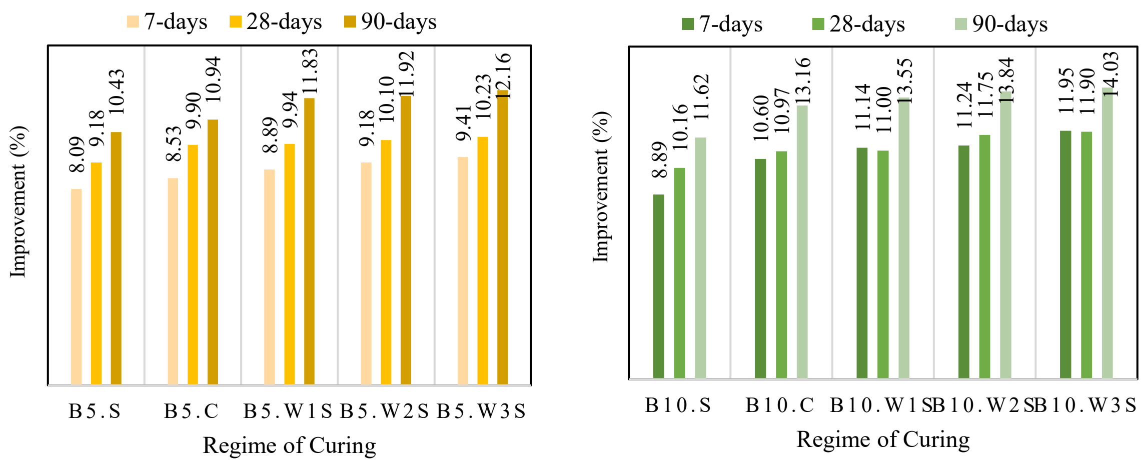
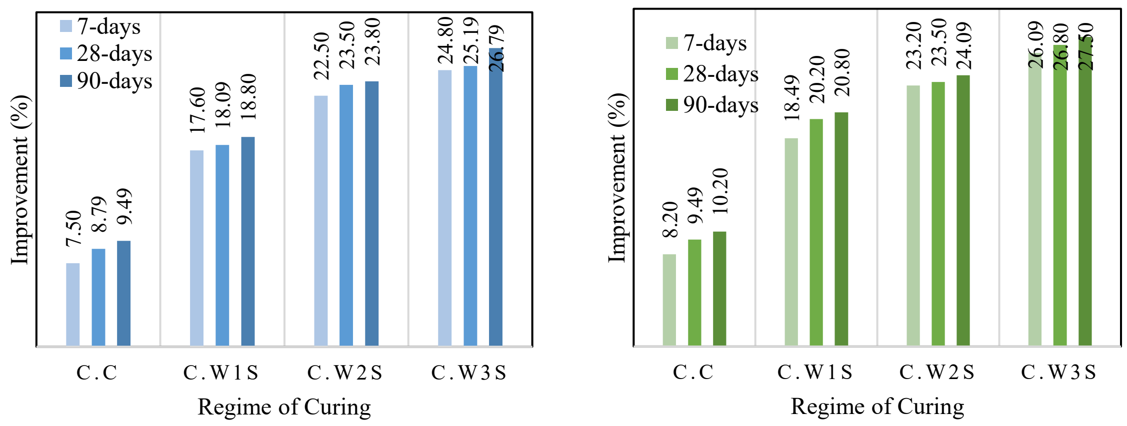


Figure 10. Comparison of the different curing systems with standard curing for sustainable mixture in compressive strength (A) B5, (B) B10.



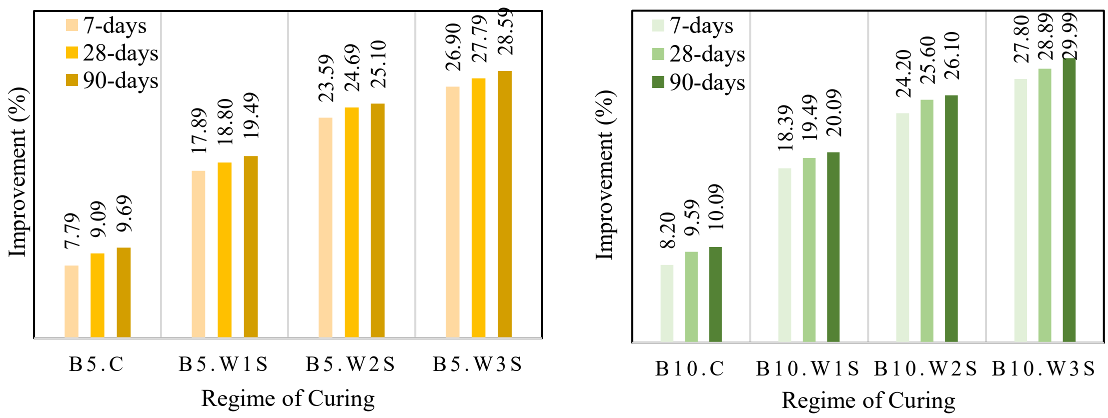
(A) **(B)**

Figure 11. Compressive strength development for the sustainable mixture compared to the control mixture for the same curing (A) B5, (B) B10



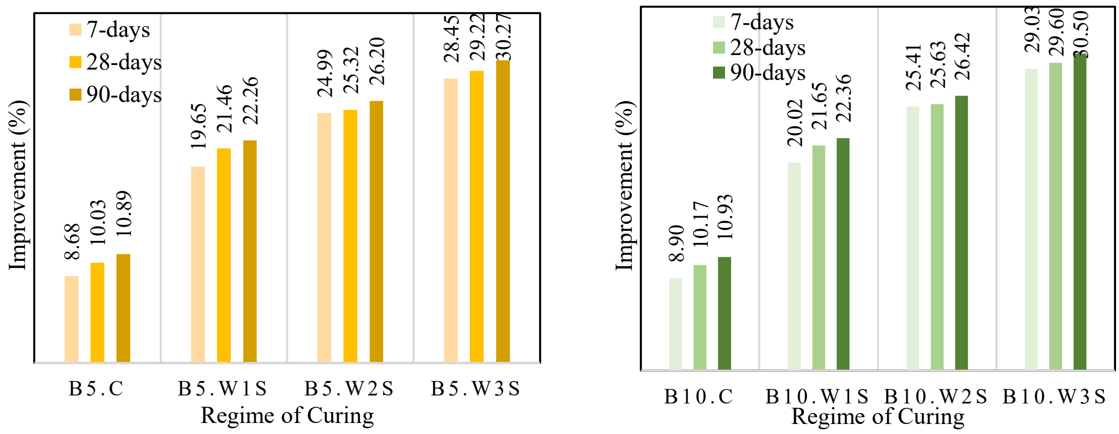
(A) **(B)**

Figure 12. Comparison of the different curing systems with standard (C.S) for control mixtures (A) Tensile strength (B) Flexural strength



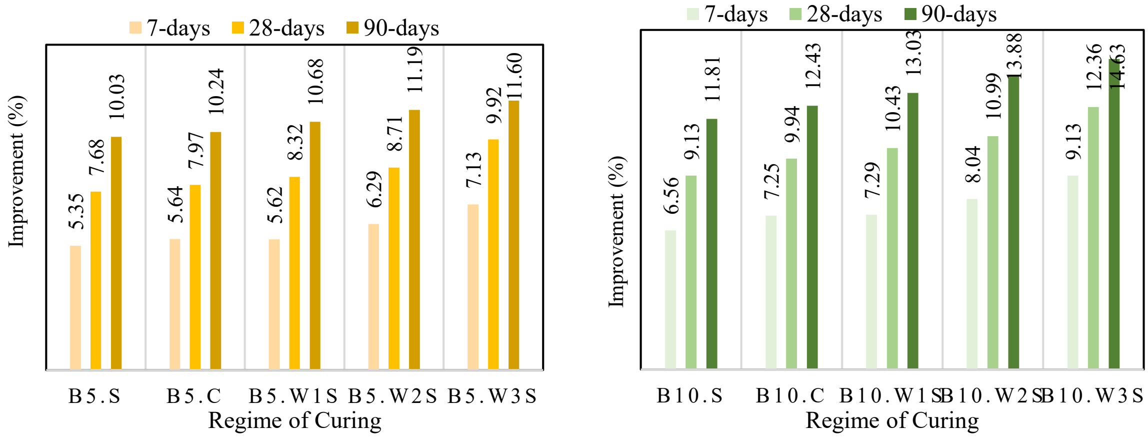
(A) **(B)**

Figure 13. Tensile strength development of sustainable mixtures in relation to various curing systems. in (A) B5, (B) B10



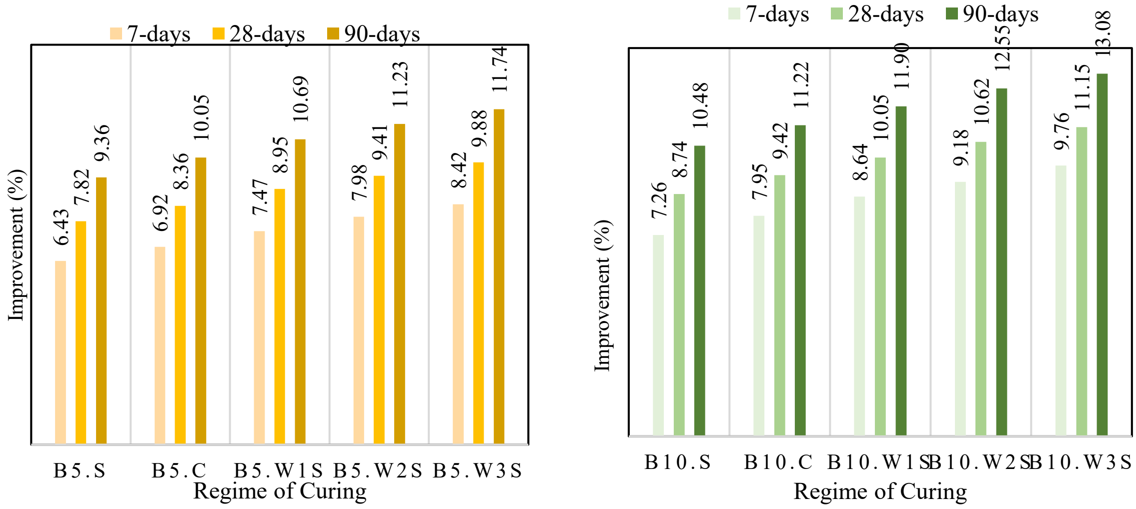
(A) **(B)**

Figure 14. Flexural strength development of sustainable mixtures in relation to various curing systems. in (A) B5, (B) B10



(A) **(B)**

Figure 15. The effects of bricks on tensile strength in (A) B5, (B) B10



(A) **(B)**

Figure 16. The effects of bricks on flexural strength in (A) B5, (B) B10

4. CONCLUSIONS

This study investigated the effect of different curing methods and the use of brick powder as a partial replacement of cement in reactive powder concrete.
The investigated lab data enable the following conclusions:

1. The capability of producing a control mixture with compressive strengths equal to 92.5, 102.9, 112.6, 115.7, and 120.1 MPa at 28 days under standard (C.S), coating (C.C), and (warm cycle + standard curing) as (C.W1S), C.W2S, and C.W3S, respectively.
2. The capability of producing sustainable RPC by using recycled waste bricks as a 5% and 10% partial replacement for cement safely with good quality and improvement in strength at all ages and different curing conditions.
3. The optimum percentage enhancement achieved by application of C.W3S (3-day warm water cycle then standard curing till 28 days) of the control mixture is equal to 29.84%, 25.19%, and 26.80% for compressive, splitting tensile, and flexural, respectively.
4. The coating using Jet Cure–GP Red material provides a suitable local field application with improvement around (11.65 ± 0.5) % for C.C, B5.C, and B10.C, respectively, at 28 days compared to standard curing.
5. The sustainable mixture incorporating 5% and 10% brick powder as a replacement for cement weight provides a good development at 28 days for all different curing conditions around (9.5 ± 0.5) % and (11.0 ± 1) %, respectively, for compressive strength.
6. The strength of splitting tensile and flexural improvement at 28 days for R-P-C mixture containing 5% and 10% brick powder shows around [(8.8 ± 0.5) % and (10.75 ± 1.5) %], respectively, for splitting and around [(8.85 ± 1) % and (9.95 ± 1) %] for flexural.
7. The harmonies and illogical results for dry density and strength, by means of an increase in compressive strength results, provide an enhancement of density, tensile splitting, and flexural.

NOMENCLATURE

Symbol	Description	Symbol	Description
A	Area, mm^2.	f_t	Splitting tensile strength, MPa.
b	Width, mm.	l	Length, mm.
D	Depth, mm.	P	Maximum failure load, N.
f_c	Compressive strength, MPa.	D	Diameter, mm
f_r	Flexural strength, MPa.	π	Pi (mathematical constant ≈ 3.1416).

Credit Authorship Contribution Statement

All authors made equal contributions to the preparation of this article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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تأثير مسحوق الطابوق كبديل جزئي للإسمنت على الخواص الميكانيكية لخرسانة المسحوق التفاعلي تحت طرق معالجة مختلفة

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الخلاصة

تهدف هذه الدراسة إلى التحقيق في تأثير طرق المعالجة المختلفة على مقاومة الخرسانة المسحوقة التفاعلية (RPC)، وكذلك تقييم استخدام مسحوق الطابوق كبديل جزئي للأسمنت. يهدف استخدام مسحوق الطابوق إلى تقليل محتوى الأسمنت واستثمار مخلفات البناء بطريقة أكثر استدامة. في هذا العمل، تم جمع الطابوق الطيني من مواقع البناء وسحقه إلى مسحوق ناعم، واستخدامه بنسب استبدال بلغت 5% و10%. تم إخضاع الخلطات لطرق معالجة مختلفة، شملت المعالجة القياسية، والمعالجة بالطلاء، والمعالجة بالماء الدافئ متبوعة بالمعالجة القياسية. تضمنت المعالجة الدافئة غمر النماذج في الماء عند درجة حرارة (35 ± 2) °م لمدة يوم واحد (W1S)، ويومين (W2S)، وثلاثة أيام (W3S)، ثم تلتها المعالجة القياسية حتى موعد الفحص. أظهرت النتائج أن مقاومة الانضغاط للخلطة المرجعية تحت المعالجة القياسية بلغت 92.5 ميغاباسكال عند عمر 28 يومًا. كما ازدادت المقاومة بنسبة 11.24%، و21.72%، و25.08%، و29.83% لكل من C.S وW1S وW2S وW3S على التوالي. بالإضافة إلى ذلك، أظهرت الخلطة المحتوية على 10% من مسحوق الطابوق أداءً أفضل، حيث سجلت زيادات في مقاومة الانضغاط بنسبة 30.94% و31.89% و32.77%، وفي مقاومة الانثناء بنسبة 29.03% و29.60% و30.50%، وفي مقاومة الشد بنسبة 27.80% و28.89% و29.99% عند أعمار 7 و28 و90 يومًا على التوالي، مقارنةً بالخلطة المرجعية. بشكل عام، تشير النتائج إلى إمكانية استخدام مسحوق الطابوق كمادة مستدامة في الخرسانة المسحوقة التفاعلية، خاصة عند دمجه مع طرق معالجة مناسبة

الكلمات المفتاحية: الخرسانة المسحوقة التفاعلية، الخرسانة المستدامة، مسحوق الطابوق الطيني، المعالجة بالطلاء، دورة العلاج دافئ ثم عادي.