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Enhancing Compressive Strength and Sustainability-High-Performance Concrete with Fly Ash and Brick Waste Powder

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ABSTRACT

This study evaluated the compressive strength of various high-performance concretes (HPCs) formulated with recycled materials such as fly ash (FA) and waste brick powder (WBP) from brick manufacturing plants. Several combinations of these additives were explored to assess their impact on the compressive strength of HPC, with measurements taken at regular intervals after curing, and slump tests to assess the workability of the concrete. The results show that materials with a high specific surface area, in particular BWP_60, significantly improve the strength and workability of concrete. However, although BWP_90 brick powder increases workability, it does not significantly improve compressive strength, and its production is more energy-intensive. This research highlighted the viability of using recycled materials to improve the properties of HPC while promoting sustainable and environmentally friendly construction practices, with particular attention to the selection and optimization of the types of materials used.

Keywords: high performance concrete, green building materials: fly ash and brick waste powder, specific surface area, compressive strength and slump.

INTRODUCTION

Cement is crucial for building but is a major energy consumer and emitter of greenhouse gases, contributing over 8% globally (Peys et al., 2022). In Morocco, cement production is around 12.5 million tons annually, exacerbated by rapid urbanization and resulting in substantial construction waste, with brick waste constituting 45% (Enviro consulting international ECI and MEVAC 2019). There are no Moroccan facilities for waste sorting or recycling, and such waste is not allowed in public landfills (Département de l'environnement – Maroc et Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ, 2019). However, research suggests that brick waste can be repurposed as a binding agent in mortar and concrete production, transforming through heat into beneficial amorphous compounds (Zhao et al., 2020; O'Farrell, Wild, and Sabir, 2001). The construction industry, driven by escalating global urbanization, is under increasing pressure to develop sustainable and durable building solutions. High-performance concrete (HPC) plays a crucial role in this innovation, recognized for its superior mechanical properties and durability. Characterized by a sophisticated blend of cementitious matrix, natural aggregates, and selective admixtures, HPC offers enhanced workability, high compressive strength, and low water-to-cement ratios. These properties not only contribute to the extended service life of reinforced concrete infrastructures but also align with the growing needs for more environmentally sustainable construction practices (Rajender and Samanta 2023; Smarzewski, 2023). By improving the resilience and efficiency of building materials, HPC addresses both current demands and future challenges in the construction industry.

The development of HPC is intricate, requiring precise adjustments in material composition and processing techniques to optimize its fundamental properties. This research undertook a detailed examination of these complexities by exploring the latest advancements and innovations in concrete technology. Notably, it addressed the contributions of alternative materials such as FA, blast furnace slag (BFS), and brick powder (BP) in enhancing the performance characteristics of concrete.

A critical review of recent studies underscores the potential of these materials in HPC formulations. For instance, research by (Ofuyatan et al., 2020) demonstrated that substituting 10% of cement with eggshell powder and blast-furnace slag significantly improves the fluidity and workability of self-compacting concrete. Additionally, increasing the substitution rate to 20% not only enhances the compressive and flexural strengths but also optimizes interfacial interactions within the concrete after 28 days of curing.

Furthermore, the study by (Hosseinzadeh et al., 2023) compared high-strength concrete and ordinary concrete, both augmented with polypropylene and steel fibers, under normal and sulfate attack conditions. The findings reveal a reduction in workability but an improvement in both compressive and tensile strengths, indicating a strategic trade-off in fiber-reinforced concrete formulations.

Moreover (Thejaswini et al., 2023) investigated the mechanical and durability properties of high-performance concrete with fine aggregates partially replaced by crushed quartzite and binders by fly ash and silica fume. This substitution showed that crushed quartzite could effectively replace up to 30% of natural sand, potentially reducing the environmental impact of concrete production.

In another study Lv et al. (2022) explored the effects of incorporating high-temperature-treated municipal solid waste fly ash into ultra-high-performance concrete (UHPC). They found that a 20% inclusion of this ash not only accelerates hydration but also enhances early compressive strength, advocating for its use as a viable cement substitute in advanced concrete applications.

Despite the proven benefits of traditional additives like silica fume in balancing workability and mechanical strength, its high cost drives the search for more economical alternatives. This study, therefore, evaluated the potential of finely ground brick powder as a novel component in HPC formulations, aiming to expand the range of sustainable materials for producing more durable and efficient concrete.

MATERIALS AND METHODS

Materials

In this study, the impact of various materials on the properties of HPC was explored. These materials include conventional aggregates such as sand and gravel, as well as innovative cementitious admixtures, such as fly ash and powder from brick waste. These also include the essential elements of cement and tap water, the latter complying with Moroccan potability standards. Additionally, the formulation incorporates Chryso® Fluid Omega S11H, a superplasticizer that meets the EN 934-2 standards, crucial for enhancing the workability and performance of concrete.

The waste bricks used come from defective bricks from a factory in Meknes. These bricks were finely ground for 60 and 90 minutes, significantly transforming their granulometry. This size reduction increased their specific surface area beyond that of traditional cement, which is crucial for concrete performance. Indeed, the increased fineness influences compaction density and the hydration process, thus directly impacting rheological properties such as slump, which measures concrete consistency and fluidity, as well as final mechanical properties, notably compressive strength, especially when PBR is used in a proportion of 5% to 15% (Letelier et al., 2018; Liu et al., 2017; Kırgız, 2016; Naceri and Hamina, 2009; Toledo Filho et al., 2007).

For ease of analysis, the particle size characterization of the materials used is set out in two tables. The first table details the particle size distribution of cement, brick powders and fly ash, providing a complete breakdown of these components. The second table deals specifically with aggregates, notably sand and gravel, illustrating their respective distributions. This classification is essential for examining the interactions between different particle sizes and assessing their influence on concrete performance. The main binder used in this study, portland-limestone cement CEM II/B-L, complies with European Union standard EN 197-1 (European Standard, 2000). This specific cement classification is widely used in the concrete industry due to its optimal balance of physical properties that contribute to concrete strength and durability. In addition, fly ash, as a supplementary cementitious material, comes from LafargeHolcim, guaranteeing the high quality and consistency of their chemical and physical characteristics.

Fly ash (FA), a residue from the combustion of coal in power stations, has been classified as an industrial waste since the 1990s (Boulday, 2016). The use of fly ash as a cement additive is regulated by standard EN-197-1, which defines composition requirements to ensure the quality and performance of cements. For this study, the class F fly ash used came from LafargeHolcim, meeting the industrial and environmental standards required for the research.

Table 1 illustrates the particle size distribution and specific surface area of various materials used in concrete manufacture. A detailed interpretation of the data for cement, two types of brick powder (BWP_60 and BWP_90), and FA is presented below:

- In the case of cement, it is notable that the majority of particles are concentrated in fractions smaller than 0.016 mm, where 60.38% of particles are present, and an even more significant proportion, 97.51%, is found in the fraction smaller than 0.001 mm. This particle size distribution profile highlights a relatively moderate fineness, with a specific surface area of 1.05 m²/g.
- Brick powder BWP_60 has a particle size distribution quite similar to that of cement, particularly in the smallest particle sizes. Indeed, it reaches 98.37% for particles smaller than 0.001 mm, a percentage slightly higher than that of cement, and has an identical specific surface area, at 1.05 m²/g. Notably, no BWP_60 particles are detected in fractions larger than 0.5 mm, indicating a particularly efficient grinding process that results in high fineness.
- Brick powder BWP_90, the result of more prolonged grinding than BWP_60, illustrates remarkable particle reduction efficiency, leaving no particles in sizes larger than 0.16 mm. It boasts a very high concentration of 97.99% in particles smaller than 0.001 mm, which is slightly lower than BWP_60, but still comparable to cement. A distinctive feature of BWP_90 is its higher specific surface area at 1.27 m²/g, compared with that of BWP_60 and cement, both at 1.05 m²/g. This increase in specific surface area can improve the reactivity of BWP_90 brick powder and enhance its role as a binder in concrete.
- FA has a more balanced particle size distribution than the other materials studied, such as cement, BWP_60 and BWP_90. They concentrate 67.35% of their particles in sizes below 0.010 mm and reach 98.29% for those below 0.001 mm, thus approaching the levels observed with brick powders and cement. However, one notable aspect of fly ash is its specific surface area, the lowest among the materials examined, at just 0.788 m²/g. This characteristic could limit their reactivity in comparison with cement and brick powders, which have higher specific surface areas.

For this research, the aggregates, including sand, were extracted from the Adarouche quarry, located in the rural commune of Aït Bourazouine, province of El Hajeb. Although each source of aggregate may have distinct characteristics influencing the properties of the concrete, those from this quarry fully meet the requirements of the NM EN 12620 standard (Table 2).

The particle size distribution table for sand and gravel clearly illustrates how these two complementary aggregates cover a wide spectrum of particle sizes, essential for obtaining cohesive, dense concrete.

Table 1. Grain size distribution of cement, BP and FA (cumulative retained mass (%))

Mesh size (mm)	2	0.8	0.5	0.16	0.08	0.016	0.010	0.001	Specific surface area (m²/g)
Cement	0	0	1.60	6.29	7.41	49.82	60.38	97.51	1.05
BWP_60	0	0	0	1.71	14.48	50.52	60.33	98.37	1.05
BWP_90	0	0	0	0	8.67	40.66	52.05	97.99	1.27
FA	0	0	0	2.68	14.5	53.46	67.35	98.29	0.788

Table 2. Grain size distribution of sand and gravel (cumulative retained mass (%))

Mesh size (mm)	31.5	20	10	6.3	2	1.25	0.63	0.08
Sand	0	0	0	0.1	43.3	64	68.5	100
Gravel	0	6.9	71.9	96.2	99	99	100	100

For sand, the majority of particles are between 2 mm and 0.08 mm. Indeed, there are virtually no particles larger than 2 mm (only 0.1% above this size at 6.3 mm), and all particles pass through the 0.08 mm sieve. This indicates that the sand is fine and is mainly concentrated in the smaller fractions, which is typical for a material used to fill the gaps between the larger particles in concrete.

Gravel, on the other hand, shows significant retention at larger sizes. No particles are retained beyond 31.5 mm, and a progressive increase is observed from 20 mm down to 6.3 mm, where 96.2% of particles are retained, reaching almost 100% at 2 mm. This shows that the gravel consists mainly of coarse particles, ideal for forming the load-bearing structure of concrete. The combination of these two distributions shows continuity in the filling of the various spaces in the concrete mix. The sand with its fine particles fills the voids left by the coarser gravel particles, improving the density and stability of the concrete. This continuous gradation of particle size is crucial to minimizing porosity and maximizing the mechanical strength of the finished concrete.

Aggregate characteristics

The quality of concrete is highly dependent on its constituents, requiring rigorous selection, particularly for aggregates. The use of local materials is recommended to minimize costs and environmental impact, while complying with regional standards. The aggregates used in this study come from the Adarouche quarry, located in the rural commune of Aït Bourazouine, in the province of El Hajeb. These aggregates meet all the requirements of the European standard NM EN 12620.

Sand equivalent

Table 3 shows the sand equivalent results for the various mixes studied. Sand equivalent is a key indicator of the quality of aggregates used in concrete production. This value quantifies the presence of fine clays and other undesirable particles that could adversely affect concrete properties such as workability or compressive strength. According to the table, the values are high, proving that the aggregates are of good quality with a low content of fine impurities. In the context of high-performance concrete, such aggregates would be preferable, as they are likely to contribute to better compressive strength and durability of the concrete.

Table 3. Sand equivalent results

Parameter	Sample 1	Sample 2	Average
Ev	94.2%	91.9%	93.0%
Ep	94.2%	93.0%	93.6%

Mechanical properties of aggregate

The gravel surface cleanliness test was carried out in accordance with the NM 10.1.169 standard, thus guaranteeing that the analysis complied with established standards. The kurtosis coefficient, a crucial indicator for assessing the grain morphology of granular materials, was measured in accordance with the NF EN 933-3/A1 standard. In addition, the Micro Deval test, which tests the abrasion resistance of aggregates in accordance with the NM EN 1097-1 standard, simulates dry friction wear through a combined action of rotation and abrasion in a cylinder containing steel balls. Finally, aggregate fragmentation resistance is assessed using the Los Angeles test, in accordance with the guidelines of the NF EN 1097-2 standard, where the test is carried out in a specific rotating drum.

Table 4 presents an assessment of the mechanical properties of aggregates, such as cleanliness, hardness (measured by Los Angeles and Micro Deval) and angularity. Consequently, the values indicate that the aggregates tested have the mechanical and geometric properties favorable to the manufacture of high-quality concrete.

Proportioning and sample preparation

In this study, in the first, seven distinct formulations of HPC were developed, each with a specific composition, identified by codes ranging from HPC0 to HPC6. Silica fume was excluded from the formulations due to its high cost. Instead, FA, a conventional cementitious substitute in concrete, was preferred and incorporated in all formulations except the control mix. HPC0, used as a reference, contains no additives. HPC1 incorporates 5% FA, HPC2 contains 10% FA, and HPC3 includes 20% FA, all in partial substitution of cement. HPC4 combines 5% FA with 10% BWP_60 brick powder. HPC5 offers a more complex formulation, using 5% FA and 10% BWP_90 brick powder. Finally, HPC6 increases the proportion of brick powder to 15% with BWP_90 to substitute part of the cement. In total, 70 specimens were prepared.

Table 4. Cleanliness, hardness and angularity

Surface cleanness (%)	Flattening coefficient in (%)	Los Angeles (LA) in (%)	Micro deval (MDE) in (%)
1.0	8	21	11

Note: Surface cleanliness (%): with a value of 1.0%, aggregates are very clean, which is good for concrete quality. Flattening coefficient (%): with a value of 8%, the flattening coefficient indicates that the aggregates are neither too flat nor too elongated, which could be good for the mechanical strength of concrete. Los Angeles (LA) (%): at 21%, it indicates fairly high resistance to wear and fragmentation. Micro deval (MDE) (%): with a value of 11%, aggregates show good resistance to degradation when exposed to freezing and thawing conditions.

Table 5 gives a detailed breakdown of the components and their respective quantities for each high-performance concrete formulation, from HPC0 to HPC6.

Table 5 shows the different formulations of HPC, varying the proportions of cement, FA and crushed brick powder (BWP). All mixes have constant proportions of gravel, sand, water and high-performance water-reducing admixtures (HRWR). Emphasis is placed on the effect of different binders (cement, FA and BWP) on concrete properties. Analysis by component is presented below:

- Cement: cement quantities vary from 452 to 564 kg, giving an idea of the levels of substitution envisaged. HPC0 is used as a control with 100% cement.
- FA: introduced into HPC1, HPC2 and HPC3 mixes, in partial substitution of cement, from 28 kg to 112 kg. This indicates an attempt to improve concrete performance and perhaps reduce costs.
- Brick waste powder (BWP_60): used in the HPC4 formulation, this powder replaces 56 kg of cement and is combined with 28 kg of FA. This choice aimed to evaluate the effectiveness of this recycled material as a cement substitute, while exploring more sustainable construction solutions.
- BWP_90: incorporated into HPC5 and HPC6 mixes, this version of brick powder, characterized by finer grain size and higher specific surface area, replaces 56 kg and 112 kg of cement respectively. The aim was to enhance concrete performance owing to these properties, although this increased fineness implies higher energy consumption than BWP_60, thus posing additional challenges in terms of energy sustainability.
- Gravel, sand, water and HRWR: these components remain constant across the mixes, eliminating their variation as a factor in the study.
- Water/cement material ratio (% W/CM): this ratio is constant at 30%, indicating that all mixes aim to have comparable workability properties.

Concrete formulations from HPC1 to HPC6 have been specifically designed to explore the possibility of reducing cement content, which is often the most costly and energy-intensive component in concrete production. The aim was to maintain or even improve the mechanical and physical properties of the final material, while optimizing costs and environmental impact. Taken as a whole, this formulation matrix provides the basis for a detailed experimental study. It aimed to assess the effects of various cement substitutes on the crucial properties of high-performance concretes, notably slump and compressive strength measured at 7 days of age. On the basis of the results obtained, the

Table 5. Proportion of mixtures

Parameter	HPC0	HPC1	HPC2	HPC3	HPC4	HPC5	HPC6
Cement (kg)	564	536	508	452	480	480	480
FA (kg)	–	28	56	112	28	28	–
BWP_60 (kg)	–	–	–	–	56	–	–
BWP_90 (kg)	–	–	–	–	–	56	84
Gravel (kg)	1070	1070	1070	1070	1070	1070	1070
Sand (kg)	640	640	640	640	640	640	640
Water (l)	170	170	170	170	170	170	170
% W/CM*	30%	30%	30%	30%	30%	30%	30%
HRWR** (l)	9	9	9	9	9	9	9

formulations that failed to meet the pre-established criteria will be eliminated from the study. For the remaining mixes, the evaluation of compressive strength will continue in order to determine their long-term effectiveness. This approach makes it possible to concentrate efforts on the most promising compositions, optimizing resources and focusing analysis on the cement substitutes that really improve the performance of high-performance concretes.

RESULTS AND DISCUSSION

Slump

Slump indicates the workability of concrete and is an important measure for understanding how the mix behaves during pouring and placing.Figure 1 shows the quantitative data for the slump tests carried out on the various high-performance concrete mixes, providing key indicators of the workability and consistency of each formulation.

The slump results presented in the table show notable variations between the different high-performance concrete (HPC) formulations, ranging from HPC0 to HPC6. Slump is an indicator of concrete workability, with higher values indicating greater fluidity.

- HPC0 shows a slump of 45 mm, indicating standard workability for common concrete uses.
- HPC1 and HPC2, which contain increasing levels of fly ash, show a slight reduction in slump at 40 mm and 30 mm, respectively. This reduction could be attributed to the incorporation of fly ash, which can absorb more water, thus reducing the fluidity of the mix.
- HPC3 has a very low slump of 25 mm, suggesting significantly reduced workability.
- HPC4, containing both fly ash and brick powder (BWP_60), shows a slump of 115 mm, indicating a significant improvement in flowability compared to previous mixes.
- HPC5 and HPC6, incorporating a higher amount of brick powder (BWP_90), show very high slumps of 195 mm and 230 mm, respectively. These extremely high values suggest excellent workability, which could be attributed to the fineness of BWP_90 improving particle distribution and reducing water demand for the same degree of fluidity.

These results demonstrate that adjusting the types and quantities of cement substitutes in concrete formulations can significantly affect the rheological properties of the mix, thus influencing both placement methods and the performance of hardened concrete.

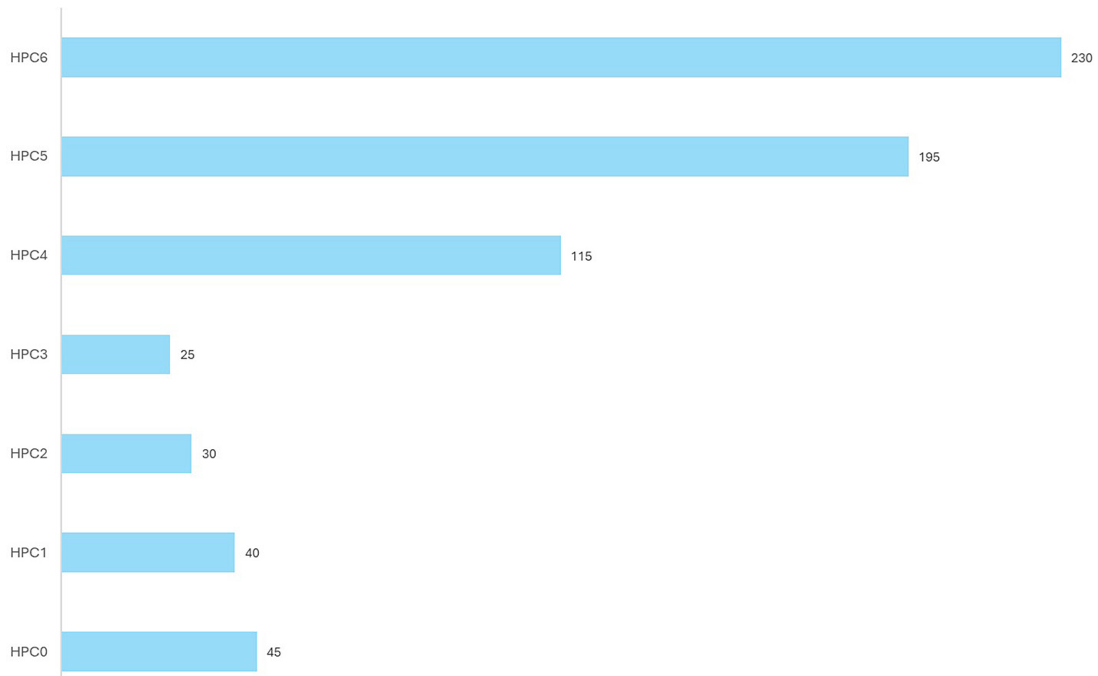

Figure 1. Slump (mm) of different HPC blends

Figure 2. Slump of specimens HPC1 and HPC6

Figure 1 shows the photographs illustrating the difference in slump between HPC1 and HPC6 mixes, with values of 40 mm and 230 mm, respectively.

This visual distinction highlights the considerable influence of the different substitute materials used in these mixes on concrete workability. In turn, the photo corresponding to HPC1 reveals a slump of 40 mm, indicating standard workability suitable for typical uses, the photo of HPC6 shows extremely high, almost free-flowing workability, with a slump of 230 mm, which could be advantageous for applications where easier concrete flow is required.

Compressive strength

The compressive strength test is the most important evaluation for determining the mechanical performance of concrete. It involves measuring the ability of concrete to resist compressive forces before breaking. In this test, concrete cylinders or cubes are placed in a compression press, such as the Automax Multitest Control Console, and subjected to an increasing load until failure occurs. The unit is equipped to exert a maximum force of 2,000 kN, ensuring precise, controlled load application, which is essential for reliable results. For each mixture, five specimens were subjected to a compression test at each specified age.

7-day results

The corresponding results are shown in Figure 3, which presents the quantitative values of compressive strength as a function of the cement substitution rate. Analysis of the 7-day compressive strength results for the different high-performance concrete formulations (HPC0 to HPC6) shows some interesting trends:

- HPC0, which is the reference formulation without any additives, has a compressive strength of 59 MPa.
- HPC1, with 5% fly ash, shows a significant increase in strength, reaching 61 MPa. This suggests that partial replacement of cement by fly ash can not only maintain but potentially improve the initial compressive strength of the concrete.
- HPC2 and HPC3, with 10% and 20% fly ash, respectively, show a decrease in strength to 56 MPa and 55 MPa. This progressive reduction could be attributed to the increase in the substitution ratio, which can adversely affect the initial cementitious matrix and reduce the efficiency of the hydration process.
- HPC4, which combines 5% fly ash and 10% brick powder (BWP_60), shows an impressive strength of 63 MPa, the highest among the formulations tested. This indicates that the synergy between fly ash and brick powder can be particularly beneficial for short-term compressive strength.

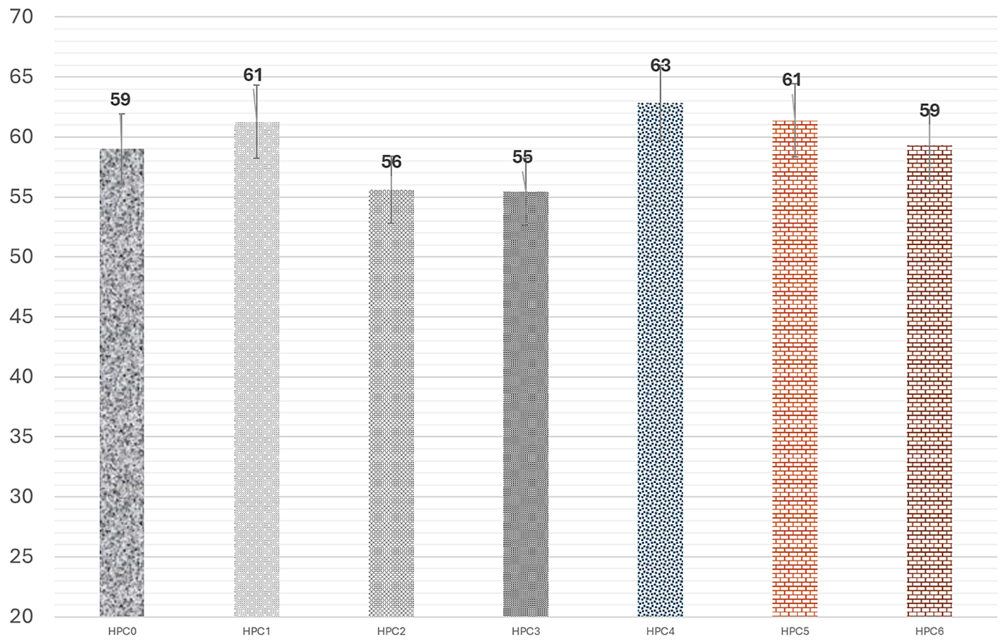

Figure 3. Compressive strength at 7 days (MPa)

- HPC5 and HPC6, using higher levels of brick powder (BWP_90), show compressive strengths of 61 MPa and 59 MPa, respectively.

Given that the compressive strengths of HPC2, HPC3, and HPC6 are below 60 MPa, and given the low slump values for HPC2 and HPC3, as well as the extremely high slump for HPC6, these three formulations will be excluded from the next 28-day compressive strength assessment. This decision allows resources to be concentrated on the mixes that offer a better balance between workability and structural performance.

28-day results

Figure 4 shows the failure modes of cylindrical samples of 16/32 and cubic samples 15/15 concrete after a 28-day curing period subjected to a compression test.

The fracture shows significant internal cohesion. A conical fracture, considered according to NM EN 12390-3 (NM EN 12390-3 IC 10.1.453 2021) as a “correct” fracture in compression tests, indicates a homogeneous stress distribution and good material strength.

Figure 5 shows the results of compressive strength tests on three high-performance concrete (HPC) mixes after 28 days of curing.

The 28-day compressive strength results for the HPC0, HPC1, HPC4, and HPC5 formulations show interesting trends and varied performance:

- HPC0 (control): this formulation, which contains no additives, has a compressive strength of 71 MPa. This is a good starting point that serves as a reference for assessing the effect of additives in other formulations.
- HPC1 (5% fly ash): compressive strength reaches 75 MPa, which represents an improvement over the control mix. This suggests that the incorporation of 5% fly ash not only compensates for the reduction in cement but can also improve the long-term properties of the concrete.
- HPC4 (5% fly ash and 10% BWP_60 brick powder): this mix has a compressive strength of 72 MPa, slightly higher than the control but slightly lower than HPC1. A slight, 4% reduction in compressive strength compared to the HPC1 mix suggests that partial replacement of cement by PBR does not necessarily compromise structural performance, in line with the opinion of some researchers Liu et al. (2017) and Duan et al. (2020), who have noted a general reduction in strength with the use of PBR. Furthermore, detailed examination of failure modes and analysis of strength data indicate that the substitution of 10% cement by PBR does not adversely affect the mechanical integrity of the mixes. These findings are in agreement with other research studies, such as those by (Olofinnade et al., 2016), which demonstrated that judicious incorporation of 10%

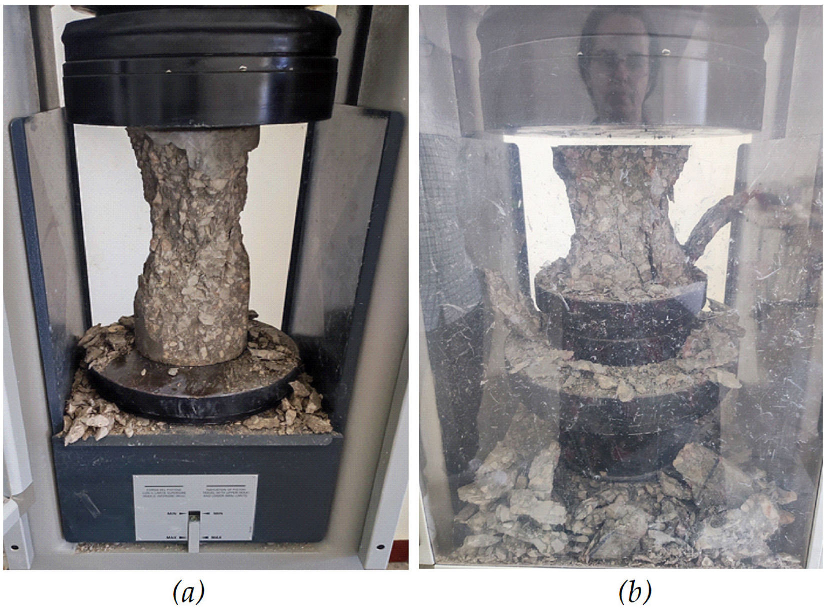

Figure 4. Concrete specimens after compression tests: (a) 16/32 and (b) 15/15

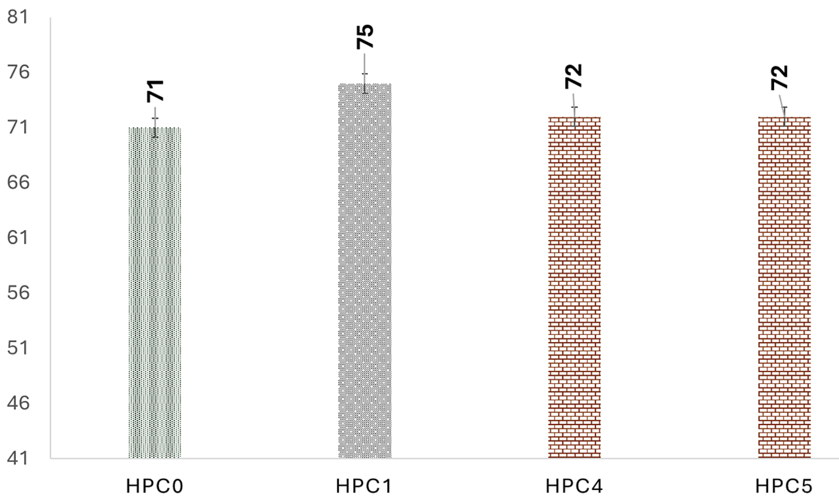

Figure 5. Compressive strength at 28 days (MPa)

PBR can improve the compressive strength of concrete at 28 days. However, these same studies showed a tendency for the strength to decrease when the percentage of PBR exceeded this threshold. On the basis of these observations, it is recommended that the substitution rate for PBR be limited to 15% in the manufacture of concrete to avoid any deterioration in mechanical properties.

- The HPC5 formulation (5% fly ash and 10% BWP_90 brick powder) has a compressive strength of 72 MPa, identical to that of HPC4, but uses BWP_90 brick powder, which consumes more energy to produce than that ground for 60 minutes (BWP_60), as demonstrated by (Abbou et al., 2023). This poses an environmental dilemma since, despite similar performance in terms of compressive strength, the increased energy footprint of BWP_90 does not justify its continued use in a context where reducing environmental impact is crucial. Indeed, if mechanical properties, such as compressive strength, do not offer significant advantages over less energy-intensive options such as BWP_60, it would make sense to favor the latter to optimize both the environmental and structural performance of concrete.

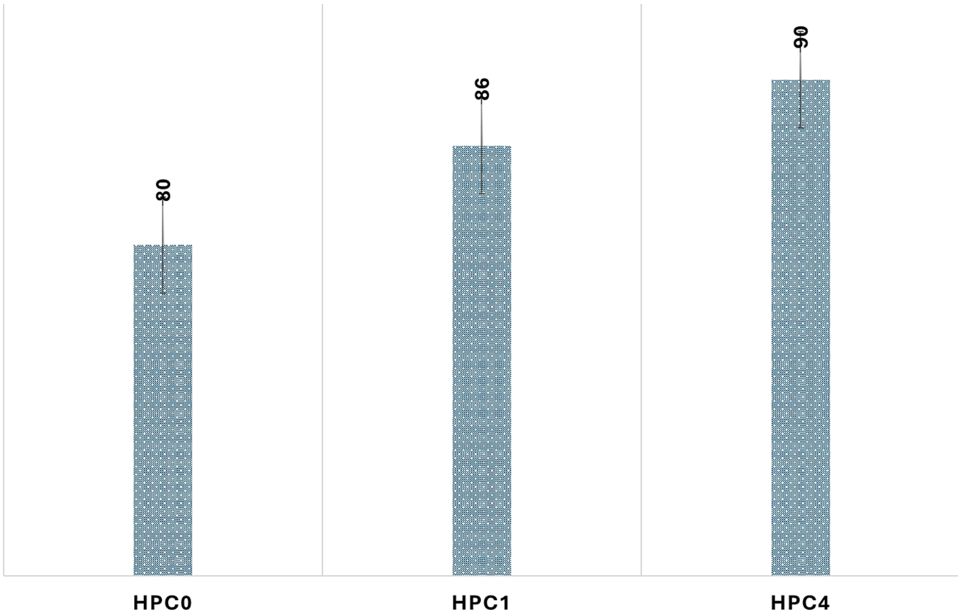

Figure 6. Compressive strength at 90 days (MPa)

With the aim of elucidating the prolonged impact of incorporating recycled brick powder (RBP) on the properties of HPC, observations at 28 days provide an initial indication of changes in mechanical characteristics. However, for a rigorous assessment of long-term durability and performance, an extended observation period is imperative.

Results at 90 days

Figure 6 shows a graph of the compressive strength of three HPC mixes after a 90 – day curing cycle. The 90-day compressive strength results for the HPC0, HPC1, and HPC4 formulations show significant improvements depending on the additives used:

- HPC0 (control): the base formulation without additives has a compressive strength of 80 MPa. This result is used as a benchmark to assess the impact of substitute materials in other mixes.
- HPC1 (5% fly ash): this formulation shows an increase in strength to 86 MPa. The incorporation of 5% fly ash appears to promote continuous improvement of the cementitious matrix over time, suggesting that fly ash contributes positively to concrete hydration and densification.
- HPC4 (5% fly ash and 10% BWP_60 brick powder): with a strength of 90 MPa, this formulation recorded the highest performance of the samples tested. The combination of fly ash and BWP_60 brick powder appears not only to compensate for the reduction in cement, but also to improve the properties of the concrete over the long term, which could be attributed to a synergy between the materials that improves the paste-aggregate interface and the overall microstructure of the concrete.

When the results obtained after 7, 28 and 90 days are compared, it becomes clear that the effect of age, combined with an increase in curing time, has a positive influence on the performance of concrete as it ages (Shao et al., 2019) studied the pozzolanic reaction of PBR in cement paste. They revealed that the pozzolanic reaction of PBR mainly occurs after 60 days, which produces additional C-A-(s)-H gels and thus a compact microstructure.

CONCLUSIONS

The obtained results indicate that BWP_60 (brick powder ground for 60 minutes) has a significant impact on both the compressive strength and workability of concrete. However, it is essential to emphasize that despite an increase in workability with BWP_90, this variant does not show any significant improvement in compressive strength and requires a higher energy expenditure than BWP_60. On the other hand, fly ash shows a constant improvement in performance and environmental sustainability. These results raise the possibility that brick powder, particularly BWP_60, could serve as a sustainable and efficient alternative in concrete production. This material offers significant benefits for recycling waste and improving the built environment, although optimizing the environmental and mechanical benefits requires an in-depth analysis of the specifics and fineness of the powder used.

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