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Technical, Environmental and Economical Assessment of Sustainable Concrete Using Waste Burnt Clay Brick Powder as Partial Replacement of Cement

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Abstract: The aim of this paper is to investigate the possibility of using waste burned clay bricks powder (WBCBPA) as a partial replacement of cement in concrete while maintaining its advantages. It is not only a materials issue, but also a construction-choice issue that involves a synthesis of strength, workability, uncertainty, cost and embodied carbon. The evidence base includes published experimental programs on flow, compressive and flexural strength, setting time, soundness, shrinkage and water-transport behavior, linked here with a clearly defined local validation program for M25 concrete, with 0%, 10%, 20% and 30% cement replacement. Two variables across the compiled studies emerge as repeated factors: the replacement level and the fineness of the processed powder. At low levels of replacement, usually in the range 5-15%, the 28-day strength of the control mix is often maintained and the relative performance sometimes improves at later ages. At 20% the response is more source-dependent, but at 30% strength and workability penalties are common. The aggregated 28-day retention values show a scatter that increases with replacement. The coefficient of variation increases from 19.4% at 10% replacement to 37.1% at 20% and 55.7% at 30%. An overall trend is described by the quadratic fit Retention (%) = 99.0 - 0.641R - 0.0371R^2, and a faster fall of the expected strength with a higher replacement is observed. In the illustrative baseline scenario, each additional 10 percentage points of WBCBP reduces the binder cost by ~7.5% and the embodied carbon by ~9.0%. But the recommendation is not based on nominal savings. Then performance, workability and reliability considerations suggest that the safest starting option is 10-15% replacement. 20% is a conditional option, to be exercised only after satisfactory local trials.
Keywords: waste burnt clay brick powder; supplementary cementitious material; sustainable concrete; embodied carbon; techno-economic analysis; multi-criteria decision analysis; construction management.

Highlights

- Low replacement levels, most often around 5–15%, show the most dependable strength response in the published record.
- At 20% replacement the outcome depends much more strongly on powder quality and fineness, while 30% behaves more as an upper-bound experimental case.
- In the base scenario, each 10 percentage points of WBCBP replacement reduce binder cost by about 7.5% and embodied carbon by about 9.0%.
- The decision should therefore be made from combined technical, statistical, economic and environmental evidence rather than from cement saving alone.

I. INTRODUCTION

Concrete will remain central to infrastructure for the foreseeable future, but its environmental burden is closely tied to Portland cement. For that reason, partial replacement of cement by supplementary materials continues to be one of the most direct ways of lowering the carbon footprint of concrete. Waste burnt clay bricks are generated in large quantities through manufacturing rejects, handling damage, site breakage and demolition. This brick-rich proportion is a typical component of construction and demolition debris in India, but much of it is currently only used in low-value applications or wasted. Once cleaned, crushed and reduced to a powder, this material becomes a viable cement replacement material instead of a waste liability. The beauty of WBCBP is that it can work in more than one way . It can act as a filler improving packing and providing nucleation sites at an early age. Later in age it can contribute a slower pozzolanic or secondary binder action because to the aluminosilicate concentration.

That contribution is not constant in scope but varies according to the original brick source, firing history, contamination, particle size, and the manner in whichthe concrete itself is proportioned and cured. Thus, the present study does not ask whether some strength is lost or gained. A wider project question is posed: how much cement can be substituted before the mix becomes difficult to place, unreliable in performance or uneconomic considering processing effort? This framing is particularly relevant in construction management where the selection of materials cannot be divorced from the grinding energy, transport, quality control, admixture demand and the risk of batch-to-batch variability.

The literature published is a useful guide but not a universal answer. The percentages of replacement are nominally similar but have given quite different results as the powders were not equally fine, equally clean or equally reactive. Some studies report little loss at low replacement and good performance at later ages, while others report early deterioration once the replacement level increases. This scatter is not a nuisance to be averaged away, but is the main motivation for a local validation program.

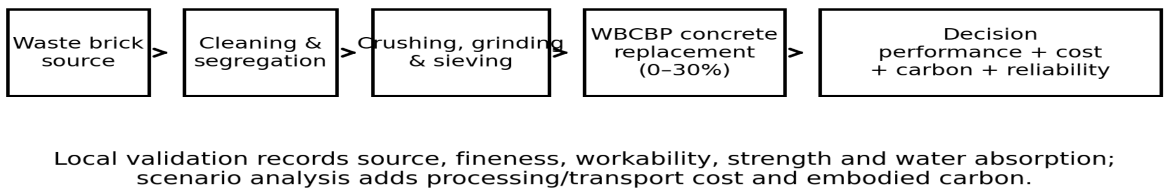


Figure 1. Integrated WBCBP processing, local-validation and construction-management decision framework

The aim of the work is to judge the technical, economic and environmental feasibility of using WBCBP as a partial cement replacement and, from that evidence, to identify a realistic working range for practice. The specific objectives are to define a compact local test programme, interpret cross-study response trends, quantify nominal cost and carbon effects, and bring these outputs together in a transparent decision framework.

II. LITERATURE REVIEW AND RESEARCH GAP

A. Sustainability context and rationale for using WBCBP

The sustainability rationale for WBCBP is simple. The embodied energy and greenhouse-gas burden of concrete is dominated by cement manufacture, so any technically acceptable reduction in clinker content is valuable [1,2]. The second sustainability benefit of brick powder is that it upgrades a mineral waste stream. Consistently, recent reviews cite fired-clay brick powder as a credible supplementary material or filler, but with a caveat that its behavior is highly source dependent [3,27,30,31]. That caveat is important: the literature is best used here as a benchmark and not as a recipe for a ready-made mix design.

Closely related materials are also known as waste brick powder (WBP), recycled brick powder (RBP), clay brick powder (CBP), ground waste clay brick (GWCB) or pulverized burned clay brick (PBCB) by different authors. In this manuscript these are considered as one broad class only when the original study deals with fired-clay brick waste ground to powder and used as a cementitious or filler replacement. Studies on coarse brick aggregate, or unfired clay or dissimilar ceramic wastes are not assumed to be directly comparable.

B. Processing variation, fineness and source

The response of WBCBP concrete is not controlled by the replacement percentage alone. Particle size, specific surface, firing history and contamination generally lead to the difference between acceptable and non-acceptable results. O'Farrell and co-workers [24–26,34] showed long ago that different brick sources give different pore structures and strength development, and later studies by Zhao et al. [5] and Ma et al. [7] confirmed that grinding finer powder can improve apparent reactivity and alter water transport as well as strength. This is why the processing route does matter in practice. The preferred sequence in the present study is source segregation, cleaning, crushing, grinding, sieving and dry storage. The aim of passing a 75 µm sieve is used as an accessible criterion wherever possible, but this is not taken as a full description of fineness; whenever possible a measurable fineness or particle-size indicator should also be recorded so that the processing effort can be related to performance at a later stage.

C. New Properties, Workability and Setting Properties

High replacement often starts to be a problem in the fresh state behavior. Many studies report that the slump or flow decreases with the increase in the amount of WBCBP due to its angular, porous particles and high effective surface area [6,12,31]. In practical terms the mix could be harder to compact before 28 day strength falls below an acceptance limit. Therefore, workability cannot be considered as a minor secondary response.

At the same time the workability trend is not strictly unidirectional. Arif et al. [29] found better workability at about 5-10% replacement, which can be attributed to the properties of the powder used in their study. These results are consistent with the broader literature, but emphasize the need for source-specific testing. They also pose a serious procedural question. More water should not be added to restore slump as it changes the water-binder ratio and thus masks the true effect of the powder. Site operations are also subject to behavior setting. In the LC3-WBP system studied by Humagain et al. [13], the initial and final setting times increased with increasing WBP content. In hot weather placing conditions a longer working time can be beneficial, but retardation of setting can also affect finishing and formwork turnover. These issues make WBCBP a project material, rather than just a laboratory curiosity.

D. Compressive, bending and tensile behavior

Compressive strength remains the most reported performance measure and the one most directly associated with routine acceptance of concrete. The literature however, records a wide dispersion. Low replacement keeps the strength close to the control and in some favorable systems, it even increases at later ages [4,8,28,29]. However, in less favorable systems, the strength uniformly decreases with increasing fraction of brick powder.The results of the PBCB mortar of Elsaigh et al. [12] clearly show that the deterioration at high replacement is progressive from 5% to 30% replacement in terms of 28 days compressive strength. Such severe losses are not universal, as indicated by reviews [3,27,31], but they do become more common when replacement exceeds roughly 20%. The observed spread is largely explained by the combined effect of cement dilution, powder fineness, water demand and source reactivity.

The flexural and splitting-tensile behavior do, in general, follow the same general trend as the compressive strength, but the sensitivity might be somewhat less at modest replacement levels. This is important since compressive strength, while useful in screening, should be confused with a complete mechanical description. Where the application envisaged is structurally demanding, the overall mechanical picture should be reviewed before a decision is made on implementation.

E. Effect of Secondary Binder and Curing Age

The literature also shows a positive trend in that the relative performance of WBCBP blends tends to improve over time. Later-age gain was attributed to pore refinement and continuing cementitious contribution by O'Farrell et al. [24–26,34]. Ortega et al. [8] reported significant 90-day development of concrete with 5–15% WBP. Likes et al. [14] reported an RBP strength activity index of approximately 92% at 7 days, 98% at 28 days and 105% at 56 days with 20% RBP. This later-age improvement does not diminish the significance of 28-day performance, but suggests that a well-processed brick powder should not be discarded based on early-age results alone. The local program uses 7 and 28 day strength as the minimum data set and recommends one later age measurement at 56 or 90 days for the preferred candidate mix.

F. Durability, water movement and shrinkage

The fineness also plays a sensitive role on the response of durability. Ma et al. [7] noted that very fine WBP, at the same replacement level of 30%, reduced capillary absorption but a much coarser powder increased it. Other studies and reviews [7,25,26,31,33] suggest that pore refinement, cure quality, and particle size can also lead to opposite trends in transport-related behavior. Water absorption is therefore a useful local indicator but it cannot be a substitute for a full durability program when the ingress of chloride, carbonation or chemical attack are critical issues.

Not all durability measures are improved. Humagain et al. [13] reported that the increase in the WBP content in an LC3-based binder led to an increase in the drying shrinkage (mainly at the highest level). The message is clear, it is not possible to select higher replacement only because it looks attractive on paper in terms of carbon or cost. Indicators related to dimensional stability and service life still need to be verified.

G. Gap in construction management and positioning of the study

The literature shows the gap in research in general. There's already plenty of evidence that brick powder can be used as a partial cement replacement under the right conditions. What is less often discussed is the practical decision-making process that links lab performance to source control, processing effort, embodied carbon, delivered cost and performance normalized efficiency. The present manuscript addresses this gap. It combines published material-level evidence with a concise local validation and decision framework for implementation, instead of just strength comparison.

Table 1. Principal experimental programmes used to frame the evidence base.

Study	System	Replacement	Relevance to this manuscript
O'Farrell et al. [24–26,34]	Ground-brick mortar	0–30%	Long-term strength, pore refinement and chemical resistance; strong source/age effects
Ge et al. [6]	GWCB concrete	10–30%	Slump; long-term strength and durability; workability loss with replacement
Letelier et al. [28]	Concrete with WBP	0–15%	Compressive/flexural strength and elastic modulus; practical low-replacement range
Ortega et al. [8]	WBP concrete	0–15%	7-, 28- and 90-day strength; favourable later-age development
Zhao et al. [5]	CBP blended cement	30%, 3 finenesses	Particle-size effect; pozzolanic activity and strength
Ma et al. [7]	WBP cement composites	Up to 30%	Strength and capillary absorption at different finenesses
Arif et al. [29]	WBP concrete	0–10%	Workability and compressive/tensile/flexural strength
Likes et al. [14]	Concrete with RBP/RCP	20%	Strength activity index to 56 d and durability-related response
Humagain et al. [13]	LC3 mortar with WBP	0, 15, 30%	Setting time, soundness, strength and shrinkage
Elsaigh et al. [12]	PBCB mortar	0–30%	Flow; 28-day compressive/flexural strength; adverse high-replacement response
Lliso-Ferrando et al. [33]	Mortar with RBP	5–45%	Strength, porosity, chloride resistance and carbonation response

III. MATERIALS AND METHODS

A. Study design and data source

The study comprises two related parts. First of all, we gather and interpret the numerical results of the published programs listed in Table 1 as benchmark evidence. The second one is the local experimental program defined for one WBCBP source collected from Rewari and Mahendergarh, Haryana. The compiled dataset can be used for identifying typical trends, variability and decision thresholds but does not replace local trial mixes. The study level statistics are used in an exploratory manner as the common secondary dataset is small and the original studies differ in binder system, powder fineness, curing regime and water-binder ratio. They are meant to indicate the direction of the trend and the uncertainty, not to be a universal predictive model for all future sources.

B. Preparation and conventional characterization of WBCBP

The raw material for the local program comes from a documented stream of waste burned clay bricks. Mortar, soil and other contaminants are removed, then the brick pieces are broken, crushed, ground and sieved. The desired product is a dry powder which passes through the 75 µm sieve where applicable. Grinding time, mass processed, electricity usage and yield are recorded for each batch, so the subsequent cost and carbon estimates are based on measured local processing, rather than generic assumptions.

The minimum characterization program is deliberately traditional. It includes data on cement specific gravity and certificate; aggregate grading, specific gravity and water absorption; and WBCBP source description, specific gravity, moisture condition and fineness indicator. Where facilities exist, more sophisticated mineralogical tests may be added, but are not required for the screening-level construction-management framework developed herein.

C. Concrete mixes and local testing program

One target concrete grade M25 proportioned as per IS 10262:2019 is the local validation matrix. Four levels of replacement by mass are considered i.e. 0%, 10%, 20% and 30% cement replacement. The first level outside the control, 10%, is the range that appears most reliable in the published record. The 20% level investigates the top band of what might still be achievable for a good powder, while 30% is retained to show upper-bound behavior, where dilution and workability penalties are often apparent.

The water content is kept constant for all the mixes. If slump control requires a superplasticizer, then one documented dosage protocol should be used for all pertinent mixtures. This makes the comparisons interpretable, since otherwise some of the difference in strength measured would be due to a changing water-binder ratio and not the effect of WBCBP.

Table 2. Local mix matrix for an illustrative binder content of 350 kg/m³.

Mix	WBCBP replacement	Cement (kg/m³)	WBCBP (kg/m³)	Total binder (kg/m³)
M0	0%	350	0	350
M10	10%	315	35	350
M20	20%	280	70	350
M30	30%	245	105	350

Table 3 is a kept a compact local test matrix. The focus is on the fresh workability and the 7 and 28 days compressive strength and 28 days water absorption, because these responses directly support the technical screening and the later decision analysis.

Table 3. Planned local validation programme.

Test	Age/condition	Standard	Replicates per mix	Minimum total
Slump	Fresh	IS 1199	≥1 per batch	≥4 observations
Compressive strength	7 days	IS 516	3	12
Compressive strength	28 days	IS 516	3	12
Water absorption	28-day / standard condition	ASTM C642 / IS-adapted	3	12

D. Statistical methods

For each hardened response, the mean, standard deviation and coefficient of variation are reported. Compressive strength is also converted to a relative strength index (RSI), obtained by dividing the strength at a given replacement level by the control strength at the same age and multiplying by 100.

At the study-comparison stage, the analysis uses descriptive statistics, exploratory ANOVA, a Kruskal–Wallis check, linear trend analysis, Spearman rank correlation and quadratic response fitting.

Once local specimen data are available, the final inference should be based on those replicate measurements rather than on the secondary study-level compilation. Assumption checks, appropriate post-hoc testing, effect-size reporting and confidence intervals are then all possible under a consistent material and curing regime.

E. Techno-economic and environmental model

The illustrative base scenario adopts a total binder content of 350 kg/m³, a cement price of ₹8/kg, a processed-WBCBP cost of ₹2/kg, a cement emission factor of 0.82 kg CO_2e/kg and a processed-WBCBP factor of 0.08 kg CO_2e/kg. These values are not presented as project quotations; they are transparent assumptions chosen to show how the framework operates before real local values are inserted.

Since unit prices and emission factors are location-sensitive, adverse and favourable scenarios are also considered in order to see whether the sign of the savings changes under less ideal conditions. The purpose of this sensitivity check is not to produce a full life-cycle assessment, but to determine whether the nominal economic and carbon advantage survives plausible variation in the inputs.

The analysis goes beyond per-cubic-metre savings. Cost per unit strength and embodied carbon per unit strength are also calculated, because a cheaper or lower-carbon concrete is not automatically a better one if it delivers substantially less structural performance. Two bounding performance cases are therefore considered: one based on the compiled mean strength retention and one based on the favourable benchmark envelope.

F. Multi-criteria decision analysis

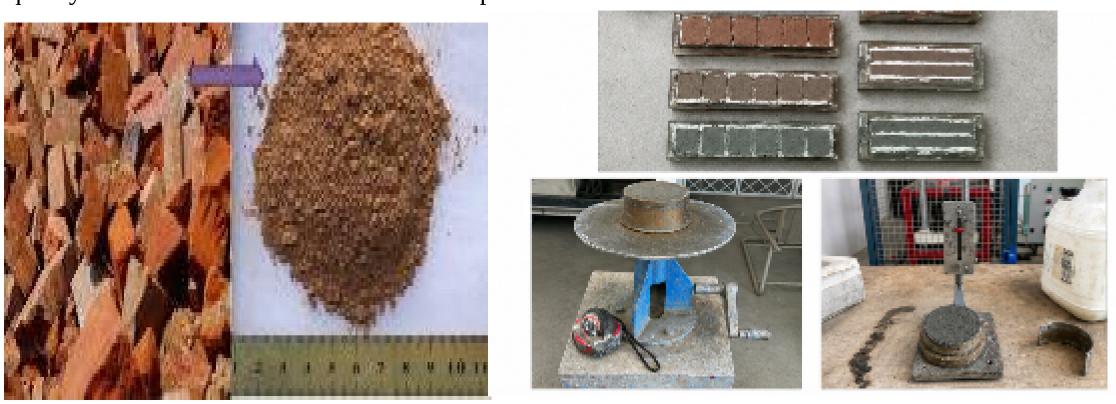
The multi-criteria framework combines five decision variables: 28-day strength retention, workability, cross-study reliability, cost and embodied carbon.

Their weights are 0.35, 0.15, 0.15, 0.175 and 0.175, respectively, so that technical performance carries the greatest combined importance. The aim is not to claim a universally correct set of weights; it is to make the trade-offs visible and to test whether the preferred replacement remains stable when the assumed source performance changes.

IV. RESULTS AND DISCUSSION

A. Synthesis of strength across studies and practical replacement range

Figure 2*b* compares the three-benchmark series at 10%, 20% and 30% replacement. The downtrend is obvious but the spread is just as important. The reported 28 day retention values at 10% replacement vary from 67.0% to 98.2%. At 20% the range is wider from 44.0% to 98.0%. At 30% the values drop to between 17.0% and 65.4%. Or, simply put, a replacement level does not account for the response. The quality of the source and the fineness of the powder still remain decisive.



(a) (b)

Figure 2(a). Waste burnt-clay brick and processed brick powder illustrating the material-preparation stage. (b) Mortar specimens, flow-table test and setting-time tests in the Laboratory

Figures 2, 2A and 2B together lend support to a practical interpretation of the evidence. The 10-15% band is the least source-sensitive area of the published record and hence the most defensible place to start local validation. For a positive, well-ground powder, a 20% replacement may still be possible, but of course there is more uncertainty. The nominal cement saving increases even further at 30% but the frequency of unfavorable outcomes is too high, to treat this level as a default recommendation. The evidence from the fresh state goes the same way. Flow loss or slump loss is typically worse when the replacement is in excess of about 10%, particularly if the powder is relatively coarse or porous. From an implementation point of view, this means that a mixture can become impractical before it becomes formally unacceptable in strength.

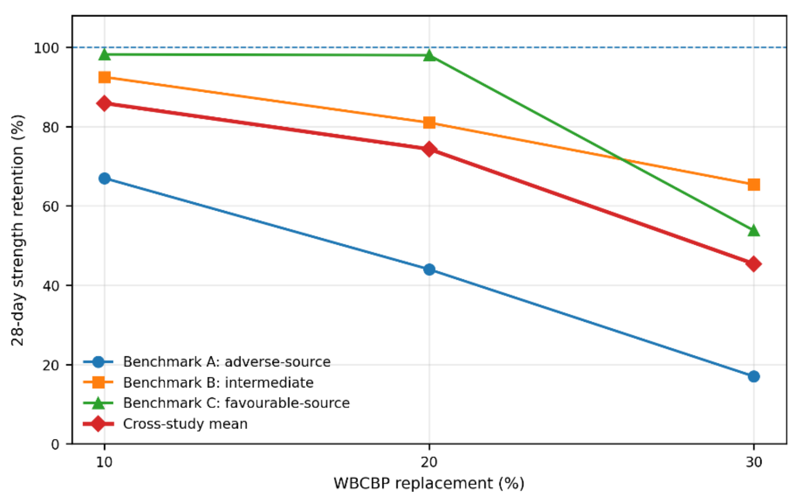


Figure 2(b). Cross-study 28-day compressive-strength retention used in the compiled benchmark dataset. The three series represent adverse, intermediate and favourable source responses included in the evidence base

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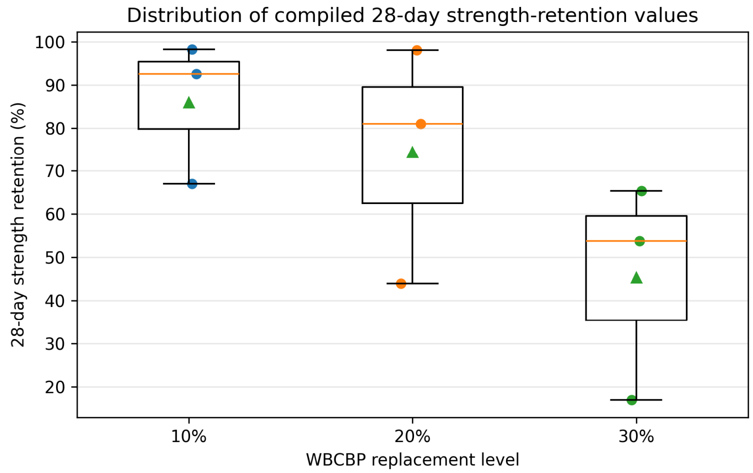

Figure 2A. Distribution of the compiled 28-day strength-retention values at 10%, 20% and 30% replacement. The mean marker and the spread together emphasize the loss of robustness at higher replacement.

Figures 2A and 2B add two further views of the same benchmark dataset. Figure 2A shows the small-sample distribution at each replacement level, while Figure 2B shows the widening envelope between the lower and upper benchmark responses.

Table 4. Descriptive statistics of 28-day strength retention across the compiled programmes.

Replacement	n	Mean retention (%)	SD (%)	CoV (%)	Range (%)
10%	3	85.91	16.63	19.4	67.0–98.2
20%	3	74.33	27.61	37.1	44.0–98.0
30%	3	45.40	25.27	55.7	17.0–65.4

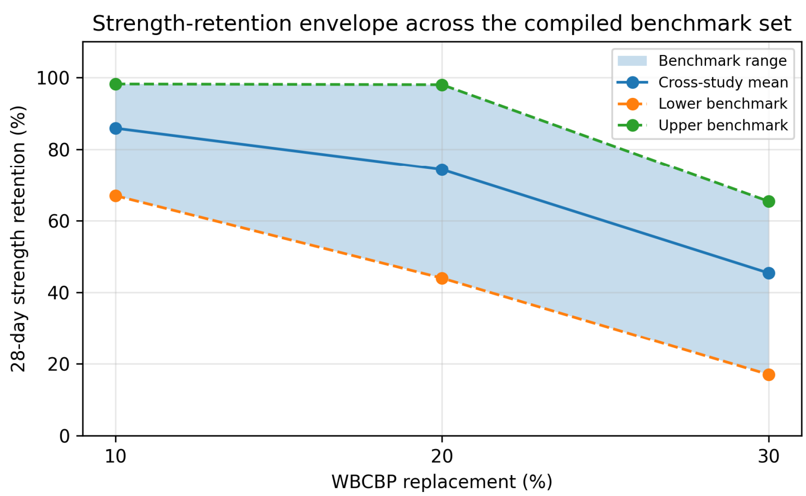

Figure 2B. Strength-retention envelope across the compiled benchmark set. The shaded band widens with replacement, showing that the uncertainty range grows at the same time as the mean response falls.

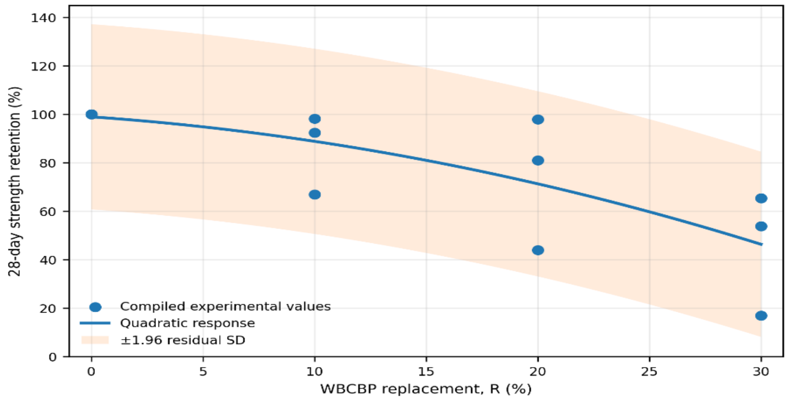

Figure 3. Quadratic response model was adjusted to the compiled 28-day strength retention values. The wide ±1.96 residual-standard-deviation band points to between-source uncertainty, and is not a prediction interval for a particular local material.

B. Response modelling

The strength-retention values with the control points were fitted with a quadratic model: Retention (%) = 99.0 − 0.641R − 0.0371R², which is applicable to the studied 0–30% range. The fit gives a R^2 of .58 and a residual standard deviation of about 19.5 percentage points. The negative squared term is useful because it captures what practitioners often observe qualitatively: the penalty for each additional increment of replacement is not constant, but tends to accelerate at higher replacement.

The fitted mean retention rates are roughly 88.9%, 71.4% and 46.4% for the 10%, 20% and 30% replacement levels. These values are descriptive, not predictive, in nature. The more important message is the width of the residual spread in Figure 3: the same nominal replacement may behave very differently from one source to another. Therefore, any decision at the project level must be based on the local powder and not only on the regression equation.

C. Workability behavior

The published results on the fresh state show a threshold-like drop of workability. At very low levels of replacement there may be little visible effect. A more obvious loss of slump tends to appear in the 10-20% range and is pronounced at 30%. The drivers are probably particle angularity, internal porosity and greater effective surface area which results in higher water demand. In practice this means that the water protocol must be kept constant and every addition of admixture must be explicitly documented.

Otherwise, the material will be judged better or worse partly because the mix water has changed and not because the powder itself was better or worse.

D. Cure age and age strength development

The intermediate benchmark dataset shows the age effect in a clear way. The 28-day retentions are about 92.5%, 81.0% and 65.4% of the control at 10%, 20% and 30% replacement respectively, while the corresponding 90-day values recover to about 98.6%, 96.7% and 89.7%. This agrees with the general trend in the literature that finely ground brick powders have a more pronounced effect at later ages.

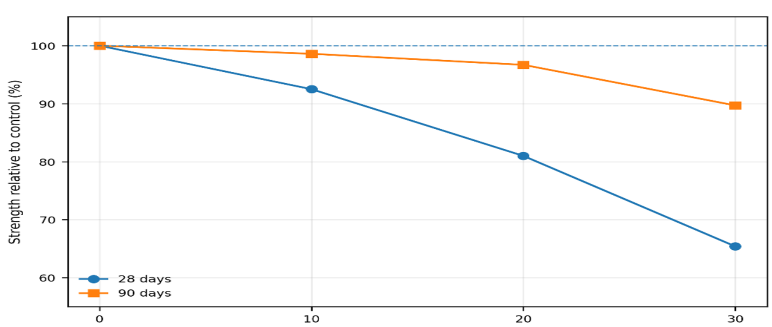

Figure 4. The effect of curing age on strength retention in the intermediate benchmark dataset is that the relative performance improves considerably between 28 and 90 days

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Later age recovery is promising but should be treated cautiously from a decision perspective. A blend that passes a good 56- or 90-day recovery might still fail in the 28-day acceptance criteria. Hence, the sensible approach is to go with 7- and 28-day results for screening, then add one later-age check for the mix that looks most promising.

E. *Fineness effect and interpretation of durability associated*

Here water absorption is used as a compact durability related indicator, since it is rather accessible and sensitive to the variations of pore-structure. But literature says that the answer is very dependent on the fineness. The same nominal substitution can lead to better or worse transport related behavior, depending on whether the powder refines the matrix or simply adds extra porosity. The contrast reported by ma et al [7] is particularly instructive. The very fine powder of the median size close to 6 µm reduced the capillary absorption by 34.1 % for replacement of 30%, while the much coarser powder of about 42 µm increased it by 10.3 %. Figure 5 illustrates this contrast and explains why fineness should be regarded as a controlled process variable and not as a casual descriptive notation.

In their results on shrinkage, Humagain et al. [13] offer a balancing caution. Their LC3-WBP mixes exhibited an increase in drying shrinkage of 56 days with increasing replacement, especially at 30%. This is a reminder that a binder that looks more sustainable does not necessarily mean that the concrete is better in use.

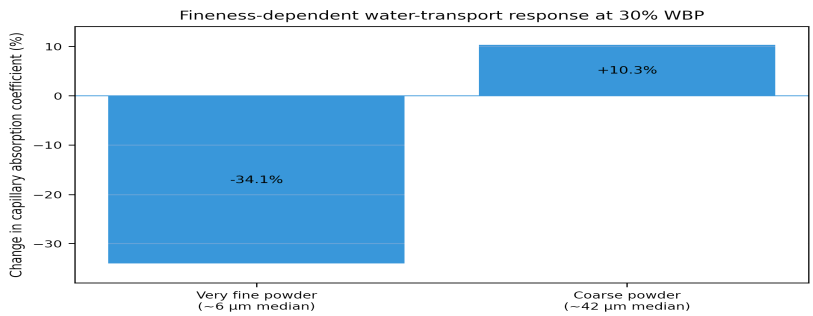

Figure 5. Fineness-dependent capillary-absorption response reported for 30% WBP [7]. Negative values indicate reduced absorption relative to the control

F. *Time of setting, soundness and related properties*

Humagain et al. [13] reported that in LC3-WBP system initial and final setting times increased with increase of WBP fraction and soundness expansion reduced. These observations apply to that binder system, but they underscore a broader point: changing out cement affects not only strength but also field productivity and dimensional stability.

The same study also demonstrated remarkable strength gain from day 7 to day 28 for all binders including the high-replacement mixture. Such gain is helpful, but must be read both in absolute and relative terms. A large relative increase from a small 7-day base is not the same as high absolute 28-day strength.

G. *Integration of Technical Interpretation*

The technical picture can most easily be understood as a competition between two sets of effects. On the positive side, fine WBCBP can improve packing, provide nucleation sites and contribute slowly reacting aluminosilicate phases. The negative side is that an increase in replacement reduces the Portland cement fraction and often increases the water demand. The dominance of one side is mainly a function of fineness, source quality, cure and the replacement level itself. Of these variables, fineness is one that can be most easily manipulated during processing. Normally the source and firing history cannot be changed after generation of the waste but the grinding intensity can be specified and monitored. The catch, of course, is that finer grinding uses more energy, and may erode part of the nominal economic and carbon advantage. Thus the fineness–energy–performance relationship is central to any realistic recommendation.

The strength-retention spread (Figure 2) and variability trend (Figure 6A) together explain why replacement percentage is a weak decision rule. As replacement increases performance on average decreases and uncertainty in that performance increases. The second of these effects is particularly important from a construction-management point of view because it translates into higher trial-mix, quality-control and acceptance risk.

This yields a working hierarchy. M10 is the validation point for low risk and should normally be the first level of replacement investigated for routine concrete. M20 is the higher benefit but higher control option. It only becomes attractive once the local powder has shown favorable strength and workability. M30 remains useful as an investigative upper bound, but the totality of evidence does not justify a routine structural-concrete recommendation.

V. STATISTICAL ANALYSIS OF THE COLLECTED EXPERIMENTAL DATA

A. *Variability and reliability of descriptive data*

As is evident from Table 4, the central statistical trend is: the average 28-day strength retention falls from 85.91% at 10% replacement to 74.33% at 20% and 45.40% at 30% replacement, while the coefficient of variation increases from 19.4% to 37.1% and then 55.7%. This increase in spread is readily apparent in Figure 6A. So, the higher replacement levels get hit twice – in lower expected performance and in less confidence in that performance.

Figure 6A shows a direct representation of the change in variability, where the coefficient of variation is plotted against replacement level.

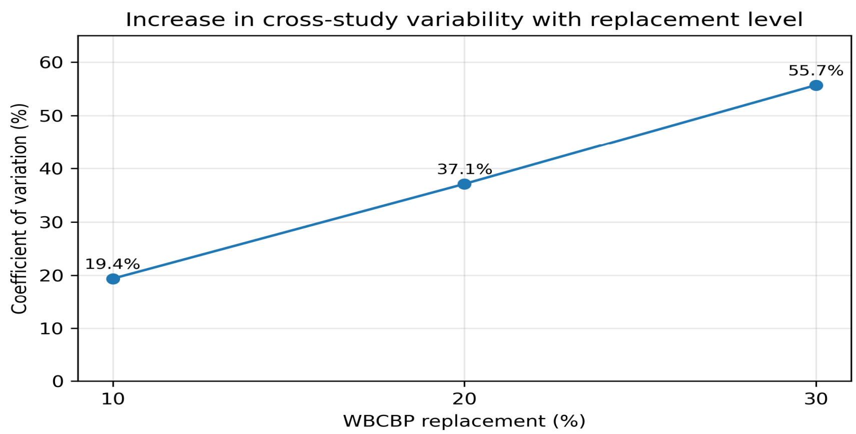

Figure 6A. Increase in cross-study coefficient of variation with WBCBP replacement. The uncertainty grows rapidly beyond 10% replacement.

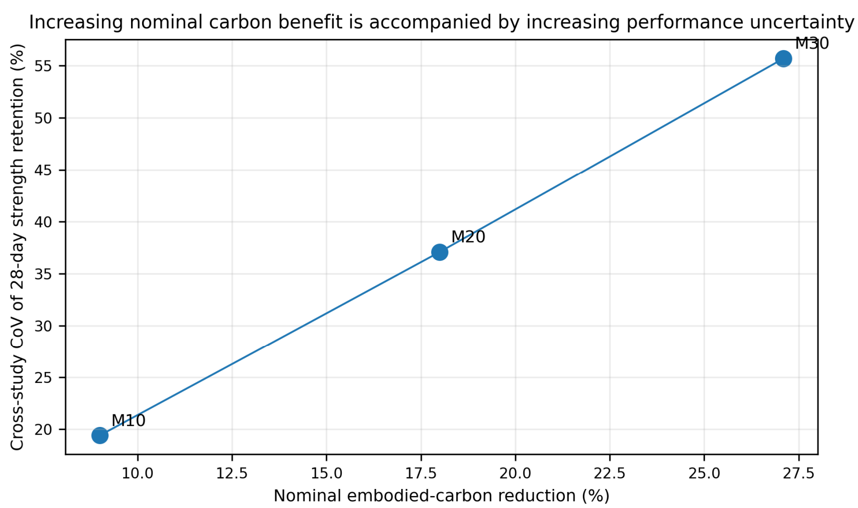

Figure 6. Decision trade-off between nominal embodied-carbon reduction and cross-study variability. Higher replacement increases nominal carbon benefit but also increases uncertainty in 28-day strength retention

The trade-off shown in Figure 6 is therefore straightforward but important. The nominal embodied-carbon saving improves steadily with replacement but so does the uncertainty in the 28-day strength. If environmental performance were the sole criterion for decision making, the analysis would lead the user to the highest replacement. That would be insufficient for the variability evidence.

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B. Exploratory inference tests

The exploratory one-way ANOVA with the three common replacement groups was not significant, F(2, 35) = 2.336, p = 0.178. This does not support a claim of statistically distinct group means in the small secondary data set at the conventional 5% significance level. This result should not be interpreted as replacement having no practical effect. This is mainly due to the small sample size and heterogeneity of the underlying studies.

The non-parametric Kruskal-Wallis test yields the same overall conclusion (H = 3.822, p = 0.148). These tests do not show that there is no material effect, but rather that strong inferential claims are fragile when only a handful of non-uniform study-level observations exist. This is exactly why the local program should be specimen-based and replicated.

C. Trend and correlation

A simple linear regression of 28-day retention on replacement level yields a slope of -2.026 retention percentage points per 1 percentage-point increase in WBCBP, or about -20.3 points per additional 10% replacement. The R^2 value corresponding to the p-value is 0.413 and 0.062, respectively. Spearman rank correlation yields $\rho = -0.685$ and $p = 0.042$, indicating a statistically significant monotonic negative association.

The linear fit is useful in showing direction, but the quadratic fit in Section 4.2 better represents the sharper fall seen at higher replacement. Neither relationship can be extrapolated beyond the 0–30% interval examined here, nor can either be used in place of local trial-mix evidence.

D. Consequences for the local experimental program

In the local program, the final inferential work should be done on the replicate samples from M0, M10, M20 and M30. This will allow for assumption checking, confidence intervals, effect-size estimates and post-hoc comparisons under a consistent protocol. With only four planned replacement levels, fitting a local response model using a quadratic form with linear and squared replacement terms is sufficient; a higher-order polynomial would not be justified.

VI. TECHNO-ECONOMIC AND ENVIRONMENTAL ASSESSMENT

A. Base scenario

The base-scenario numbers are simple but informative. With 350 kg/m³ total binder, the control mix has an estimated binder cost of ₹2800/m³ and embodied carbon of 287.0 kg CO_2e/m³.

At 10% replacement these reduce to ₹2590/m³ and 261.1 kg CO_2e/m³; at 20%, to ₹2380/m³ and 235.2 kg CO_2e/m³; and at 30%, to ₹2170/m³ and 209.3 kg CO_2e/m³. Under the fixed assumptions, the trend is almost perfectly linear because the unit rates and emission factors are kept constant.

Table 5. Base-scenario binder cost and embodied carbon.

Replacement	Binder cost (₹/m³)	Embodied carbon (kg CO_2e/m³)	Cost reduction	Carbon reduction
0%	2800	287.0	0.0%	0.0%
10%	2590	261.1	7.5%	9.0%
20%	2380	235.2	15.0%	18.0%
30%	2170	209.3	22.5%	27.1%

Figures 7A and 7B separate the performance-normalized comparison into cost per unit strength and embodied carbon per unit strength. A value below 1.0 indicates an improvement over the control.

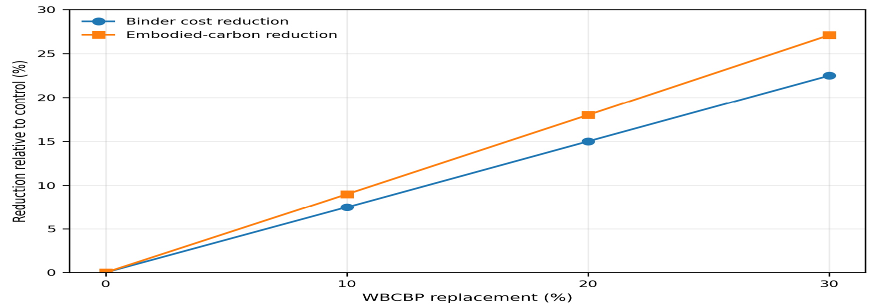

Figure 7. Base-scenario binder cost and embodied-carbon reductions relative to the control. The savings increase approximately linearly because the scenario uses fixed unit prices and emission factors

These numbers explain the initial appeal of WBCBP – in the scenario, the processed powder is cheaper and less carbon intensive than the cement it replaces. Simultaneously, the calculation is intentionally restricted to binder level effects. A project-level assessment also includes collection, transport, crushing, grinding, sieving, storage, testing and any additional admixture demand.

B. Carbon abatement: economics and sensitivity

The size of the saving is dependent on the assumed input values but the sign of the saving does not change as long as processed WBCBP is cheaper and lower-carbon than cement. Even at the adverse price set used in the manuscript (cement at ₹7/kg and WBCBP at ₹3/kg), 10% replacement still resulted in a binder-cost saving of the order of 5.7%. The 10% carbon reduction also stays close to the 8–9% range under the considered factor variations.

The economics of carbon abatement is interesting. In the base case, M10 avoids around 25.9 kg CO2e per cubic meter while saving ₹210 i.e. a monetary saving of approx. ₹8.1 per kg CO2e avoided. Under the stated assumptions WBCBP then can be viewed as a negative-cost abatement measure in that sense. The nominal abatement value does not become uncertain at higher replacement, but the engineering performance that comes with it does.

C. Performance-normalized metrics

When the delivered strength varies considerably savings per cubic meter are not enough. Thus, Table 6 and Figures 7A and 7B compare the alternatives using the mean-retention case and the favourable-source case based on the normalized cost per unit strength and the normalized embodied carbon per unit strength. This framing is more stringent, since it asks whether the user gets better structural efficiency, as opposed to just lower binder consumption.

Figures 7A and 7B separate the performance-normalized comparison into cost per unit strength and embodied carbon per unit strength. A value below 1.0 indicates an improvement over the control.

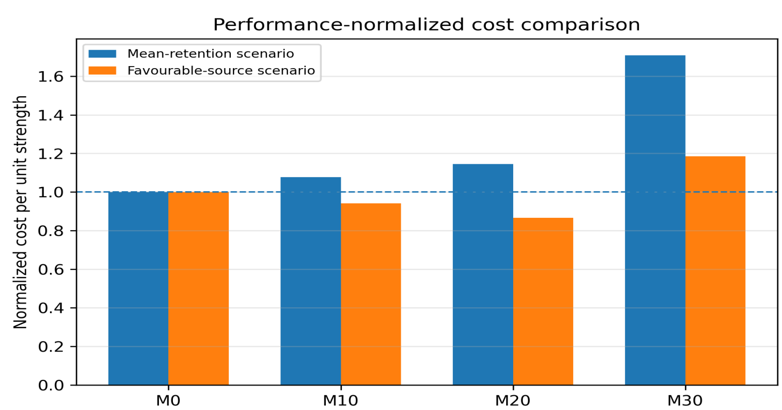

Figure 7A. Performance-normalized cost comparison. Under the mean-retention case, all replacement levels exceed the control value of 1.0; under the favourable-source case, M10 and M20 fall below 1.0.

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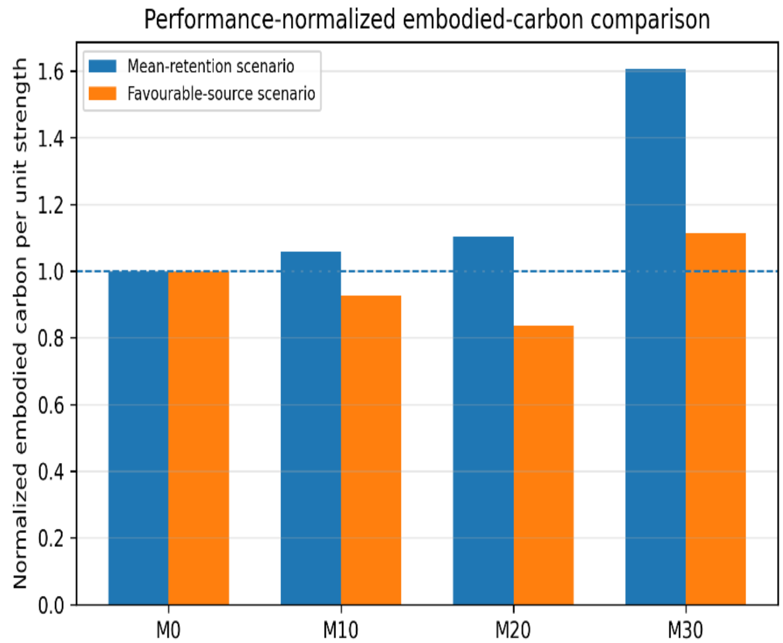

Figure 7B. Performance-normalized embodied-carbon comparison. The ranking mirrors the cost-based result and again shows that nominal savings must be checked against delivered strength

Table 6. Performance-normalized cost and carbon indices (control = 1.000; lower is better).

Mix	Cost/m³ index	Cost/unit strength (mean)	Cost/unit strength (fav.)	Carbon/unit strength (mean)	Carbon/unit strength (fav.)
M0	1.000	1.000	1.000	1.000	1.000
M10	0.925	1.077	0.942	1.059	0.926
M20	0.850	1.144	0.867	1.103	0.836
M30	0.775	1.707	1.185	1.606	1.115

The result is revealing. Under mean cross-study retention, every replacement level performs worse than the control on both cost-per-strength and carbon-per-strength, despite the nominal per-cubic-metre savings. Under the favourable-source scenario, M10 and M20 become better than the control, whereas M30 remains inferior. Source quality therefore determines whether the apparent savings are converted into delivered structural efficiency.

D. Multi-criteria decision analysis

The weighted multi-criteria analysis gives another way of reading the same trade-off. With the stated weights, the mean-retention scores are 0.650 for M0, 0.650 for M10, 0.681 for M20 and 0.618 for M30. Under the favourable-source case the scores become 0.650, 0.693, 0.764 and 0.688, respectively.

The ranking should be read, however, in conjunction with robustness. In the mean-retention case, M20 only just beats M0 and M10, and with much weaker reliability. The strongest option for the favourable-source case is M20, which offers high nominal benefit and good retained performance. The M10 recommendation is the most robust, since its acceptability is least sensitive to optimistic assumptions.

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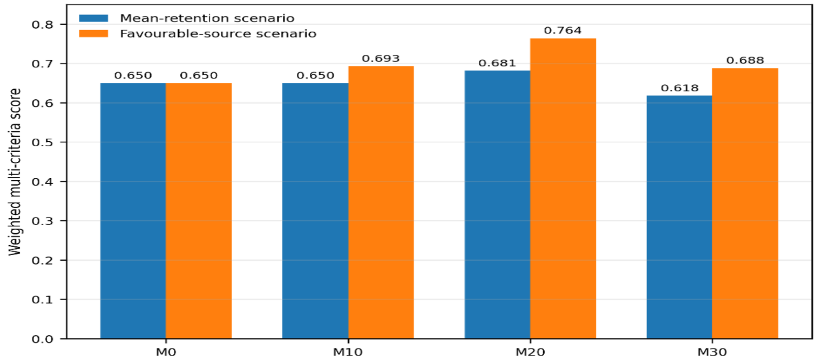

Figure 8. Multi-criteria weighted totals under mean-retention and favourable-source performance scenarios

The value of the MCDA does therefore not lie in providing a single immutable answer. Its value is that it lays bare the trade-offs. A choice based only on strength would understate cost and carbon benefits, a choice based only on sustainability would overstate them, and a simple average score without accounting for reliability would hide the additional uncertainty that accompanies higher replacement.

E. Local implementation practical requirements

Replace all illustrative inputs with project specific values before field implementation. Local cement price, electricity tariff, grinding capacity, labor, transport distance, yield loss and admixture demand should be obtained or measured using reliable quotations. For each batch the source of brick, contamination, moisture condition and fineness should also be recorded. Make trial mixes with constant batching, water control and curing conditions. Control and WBCBP mixes should be prepared from the same source of aggregate and tested using the same procedures. Record slump fresh density, admixture dosage, 7- and 28- days compressive strength and water absorption. Only technically acceptable mixes should be subjected to economic and environmental assessment, using the measured local strength to recalculate the savings and performance-normalized indices. Where possible, it is also recommended to perform a 56- or 90-day compressive-strength test for the selected mix. The strength at a later age can better illustrate the performance of well-processed WBCBP, particularly near the 20% replacement level.

Table 7. Practical checks before adopting WBCBP in a project.

Stage	Minimum information to record	Purpose	Basis for proceeding
Source and cleaning	Brick source; visible contamination; removal of mortar, soil and foreign matter	Limit uncontrolled source variation	A clean and documented waste stream is available
Powder processing	Grinding duration; mass processed; yield; electricity use; fineness or % passing 75 µm	Relate material quality to processing effort and energy	Target fineness and dry-storage condition are achieved
Trial mixes	Slump; admixture dosage; 7- and 28-day strength; water absorption	Check performance under one common protocol	Fresh and hardened properties are acceptable with reasonable scatter
Cost and carbon	Local cement and WBCBP processing rates; transport; electricity; adopted emission factors	Replace illustrative assumptions with project values	Measured mixture remains beneficial after strength normalization
Later-age confirmation	56- or 90-day strength for the selected mixture, where practicable	Check the slower strength contribution reported for WBCBP	Later-age response supports the selected replacement level

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VII. CONCLUSIONS AND FUTURE WORK

A. *Conclusions*

1) The data acquired proves that WBCBP can be a technically feasible partial cement-replacement material. But its application is not limited to the nominal replacement percentage. The quality of the waste source, the fineness of the processed powder and the way in which the concrete is proportioned and cured are the controlling variables.
2) The range of the replacement with the most reliable performance is around 5-15% in benchmark studies. During this time, several reported systems demonstrated compressive strength approaching control levels and even better performance at later age.
3) Some studies find that the average performance is still workable with 20% replacement but the scatter is much larger. The resulting coefficient of variation increases to 37.1%, which means that local validation is no longer optional, it is essential.
4) Unfavorable balance at 30% replacement in many cases. Large workability and strength penalties become common and the adverse benchmark retained only 17% of the control 28 day strength. Thus, this level is more appropriate as an upper experimental comparison than as a routine structural-concrete recommendation.
5) Workability tends to decrease as the content of WBCBP increases, particularly at replacement levels higher than about 10 to 20 percent. Don't lightly increase water to compensate for this effect. If admixture is required the dosage should be controlled, reported and taken into account in the latter economic comparison.
6) Recovery of strength at late age is a common positive characteristic of WBCBP systems. Accordingly, 7- and 28-day strength should be supplemented by one laterage measurement of the selected candidate mix, where practicable.
7) Water-transport behavior is highly dependent on fineness. The literature reports both improvement and deterioration at the same nominal replacement level, suggesting that fineness should be specified and monitored as a process parameter, rather than simply being described post hoc.
8) The quadratic fitted to the compiled 28-day data is useful as a descriptive summary and indicates an accelerating loss with replacement, but has a large spread in its residuals. It's used to set expectations, not replace local testing.
9) In the base techno-economic scenario, every 10% additional replacement of WBCBP reduces binder cost by approximately 7.5% and embodied carbon by approximately 9.0%. Under these assumptions the substitution is a carbon abatement measure with negative costs.
10) The simple ranking changes if the savings are normalized by the strength achieved. When local performance is only average, none of the replacement levels outperforms the control per unit strength. If the local powder is close to the favorable benchmark, both M10 and M20 are attractive.

Overall, the combined technical, statistical and decision analysis supports M10 as the most robust starting point and M20 as a conditional upgrade for a favorable local source. So, the key decision variable is not just replacement percentage but the combination of source quality, fineness, reliability, cost and carbon.

B. *Limitations and future scope*

The main limitation of the current manuscript is the size and heterogeneity of the compiled benchmark dataset. Exploratory statistics can be useful to help identify the direction of trends and their spread, but they are not a substitute for a local replicated study.

Similarly, the cost and carbon calculations are scenario based rather than measured values for the project, and water absorption is used here as a minimum indicator related to durability rather than a complete assessment of service life.

Future work should therefore extend the local program in three directions, firstly by testing a second brick-waste source so that source-to-source variability can be quantified; secondly by comparing at least two grinding levels to map the fineness-energy-performance trade-off more clearly; and thirdly by adding a more transport-sensitive durability test such as sorptivity or chloride penetration for the selected mixture. The linking of measured electricity consumption and transport distance to a collection-radius model would also transform the present scenario framework into a more project-specific decision tool.

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REFERENCES

[1] Scrivener, K.L., John, V.M., Gartner, E.M. (2018). Eco-efficient cements: Potential economically viable solutions for a low-CO_2 cement-based materials industry. Cement and Concrete Research, 114, 2–26.

[2] Habert, G., Miller, S.A., John, V.M., Provis, J.L., Favier, A., Horvath, A., Scrivener, K.L. (2020). Environmental impacts and decarbonization strategies in the cement and concrete industries. Nature Reviews Earth & Environment, 1, 559–573.

[3] SallıBideci, Ö., Bideci, A., Ashour, A. (2024). Utilization of recycled brick powder as supplementary cementitious materials—A comprehensive review. Materials, 17, 637.

[4] Naceri, A., Hamina, M.C. (2009). Use of waste brick as a partial replacement of cement in mortar. Waste Management, 29, 2378–2384.

[5] Zhao, Y., Gao, J., Liu, C., Chen, X., Xu, Z. (2020). The particle-size effect of waste clay brick powder on its pozzolanic activity and properties of blended cement. Journal of Cleaner Production, 242, 118521.

[6] Ge, Z., Wang, Y., Sun, R., Wu, X., Guan, Y. (2015). Influence of ground waste clay brick on properties of fresh and hardened concrete. Construction and Building Materials, 98, 128–136.

[7] Ma, Z., Tang, Q., Wu, H., Xu, J., Liang, C. (2020). Mechanical properties and water absorption of cement composites with various fineness and contents of waste brick powder from C&D waste. Cement and Concrete Composites, 114, 103758.

[8] Ortega, J.M. et al. (2018). Influence of waste brick powder in the mechanical properties of recycled aggregate concrete. Sustainability, 10, 1037.

[9] Li, L.G., Lin, Z.H., Chen, G.M., Kwan, A.K.H. (2020). Reutilizing clay brick dust as paste substitution to produce environment-friendly durable mortar. Journal of Cleaner Production, 274, 122787.

[10] He, Z., Shen, A., Wu, H., Wang, W., Wang, L., Yao, C., Wu, J. (2021). Research progress on recycled clay brick waste as an alternative to cement for sustainable construction materials. Construction and Building Materials, 274, 122113.

[11] Wang, H., Wang, L., Qian, X., Cao, K., Xu, Y., Fang, Y., Cui, L. (2022). Hydration, compressive strength and durability of eco-friendly cement mortars containing recycled brick powder and metakaolin. KSCE Journal of Civil Engineering, 26, 4023–4037.

[12] Elsaigh, W.A., Tshetlanyane, P.A., Asteray, D.B., Mitikie, B.B. (2026). Sustainable construction materials: Potential use of pulverised burnt clay bricks as a partial replacement of Portland cement. RILEM Bookseries, 72, 116–124.

[13] Humagain, S., Shrestha, G., Madhavan, M.K., Sarker, P.K. (2025). Hydration, soundness, and strength of low carbon LC3 mortar using waste brick powder as a source of calcined clay. Materials, 18, 3697.

[14] Likes, L., Markandeya, A., Haider, M.M., Bollinger, D., McCloy, J.S., Nassiri, S. (2022). Recycled concrete and brick powders as supplements to Portland cement for more sustainable concrete. Journal of Cleaner Production, 364, 132651. https://doi.org/10.1016/j.jclepro.2022.132651.

[15] Turanli, L., Bektas, F., Monteiro, P.J.M. (2003). Use of ground clay brick as a pozzolanic material to reduce the alkali-silica reaction. Cement and Concrete Research, 33, 1539–1542.

[16] Navrátilová, E., Rovnaníková, P. (2016). Pozzolanic properties of brick powders and their effect on the properties of modified lime mortars. Construction and Building Materials, 120, 530–539.

[17] Aliabdo, A.A., Abd-Elmoaty, A.M., Hassan, H.H. (2014). Utilization of crushed clay brick in concrete industry. Alexandria Engineering Journal, 53, 151–168.

[18] Bektas, F., Wang, K., Ceylan, H. (2009). Effects of crushed clay brick aggregate on mortar durability. Construction and Building Materials, 23, 1909–1914.

[19] IS 456:2000. Plain and Reinforced Concrete—Code of Practice. Bureau of Indian Standards, New Delhi.

[20] IS 10262:2019. Concrete Mix Proportioning—Guidelines. Bureau of Indian Standards, New Delhi.

[21] IS 383:2016. Coarse and Fine Aggregate for Concrete—Specification. Bureau of Indian Standards, New Delhi.

[22] IS 516. Method of Tests for Strength of Concrete. Bureau of Indian Standards, New Delhi.

[23] IS 1199. Methods of Sampling and Analysis of Concrete. Bureau of Indian Standards, New Delhi.

[24] O'Farrell, M., Wild, S., Sabir, B.B. (2001). Pore size distribution and compressive strength of waste clay brick mortar. Cement and Concrete Composites, 23(1), 81–91. https://doi.org/10.1016/S0958-9465(00)00070-6.

[25] O'Farrell, M., Wild, S., Sabir, B.B. (1999). Resistance to chemical attack of ground brick-PC mortar, Part I: Sodium sulphate solution. Cement and Concrete Research, 29, 1781–1790. https://doi.org/10.1016/S0008-8846(99)00170-2.

[26] O'Farrell, M., Wild, S., Sabir, B.B. (2000). Resistance to chemical attack of ground brick-PC mortar, Part II: Synthetic seawater. Cement and Concrete Research, 30, 757–765. https://doi.org/10.1016/S0008-8846(00)00245-3.

[27] Wong, C.L., Mo, K.H., Yap, S.P., Alengaram, U.J., Ling, T.-C. (2018). Potential use of brick waste as alternate concrete-making materials: A review. Journal of Cleaner Production, 195, 226–239. https://doi.org/10.1016/j.jclepro.2018.05.193.

[28] Letelier, V., Tarela, E., Moriconi, G. (2017). Mechanical properties of concretes with recycled aggregates and waste brick powder as cement replacement. Procedia Engineering, 171, 627–632. https://doi.org/10.1016/j.proeng.2017.01.396.

[29] Arif, R., Khitab, A., Kırgız, M.S., Khan, R.B.N., Tayyab, S., Khan, R.A., Anwar, W., Arshad, M.T. (2021). Experimental analysis on partial replacement of cement with brick powder in concrete. Case Studies in Construction Materials, 15, e00749. https://doi.org/10.1016/j.cscm.2021.e00749.

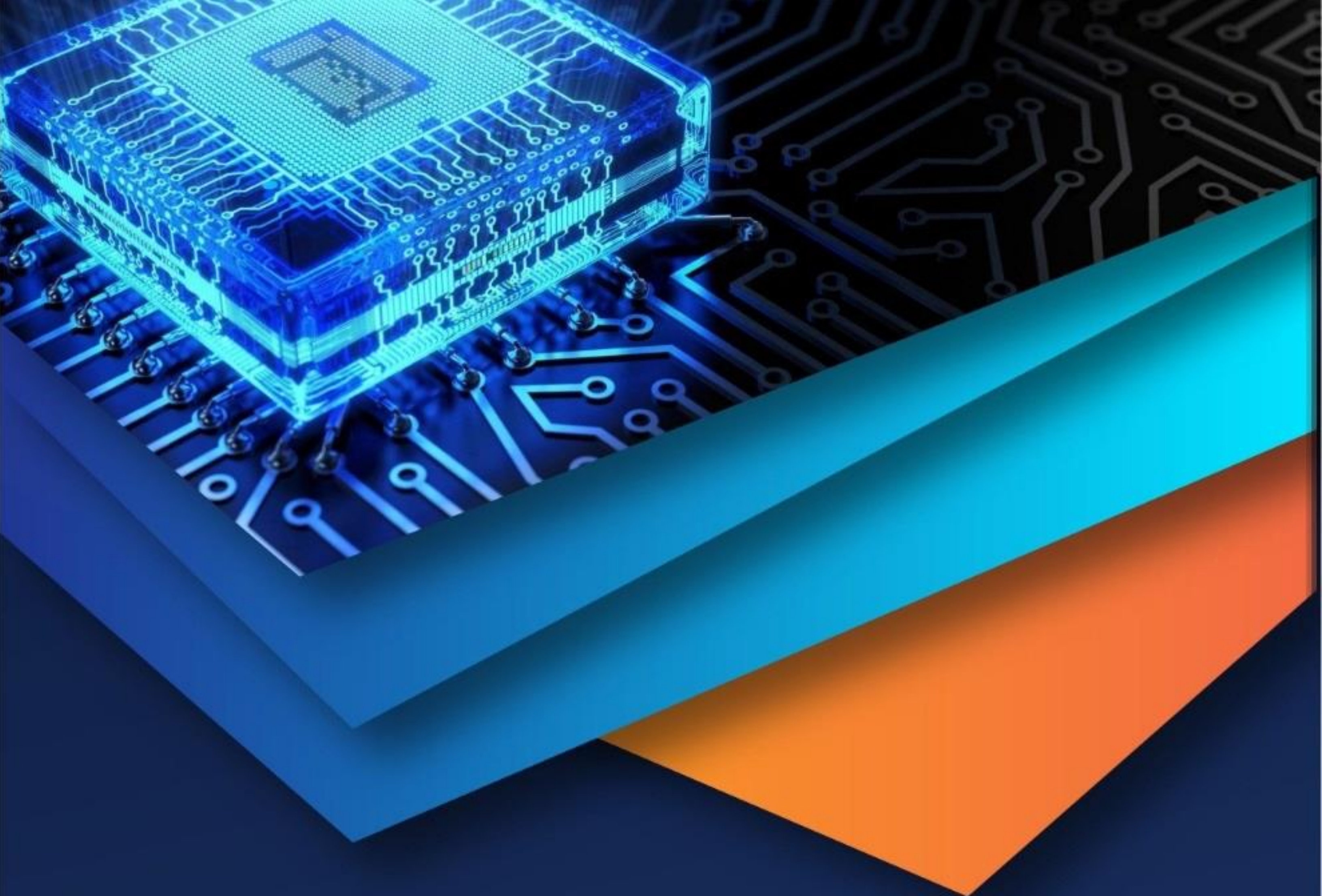
[30] Zhu, L., Zhu, Z. (2020). Reuse of clay brick waste in mortar and concrete. Advances in Materials Science and Engineering, 2020, 6326178. https://doi.org/10.1155/2020/6326178.

[31] Hu, J., Ahmed, W., Jiao, D. (2024). A critical review of the technical characteristics of recycled brick powder and its influence on concrete properties. Buildings, 14(11), 3691. https://doi.org/10.3390/buildings14113691.

[32] Rumiński, P., Szeląg, M., de Matos, P. (2022). Evaluating the feasibility of using brick powder and clay powder in cement replacement. Materials, 15(22), 8127. https://doi.org/10.3390/ma15228127.

[33] Lliso-Ferrando, J.R., Arenós-Barrachina, A., Monzón-Bello, P., Valcuende, M. (2025). Durability of mortars with partial cement replacement by recycled brick powder. Applied Sciences, 15(8), 4133. https://doi.org/10.3390/app15084133.

[34] O'Farrell, M., Sabir, B.B., Wild, S. (2006). Strength and chemical resistance of mortars containing brick manufacturing clays subjected to different treatments. Cement and Concrete Composites, 28(9), 790–799. https://doi.org/10.1016/j.cemconcomp.2006.05.014.



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