World Journal of Advanced Engineering Technology and Sciences
eISSN: 2582-8266
Cross Ref DOI: 10.30574/wjaets
Journal homepage: https://wjaets.com/

(REVIEW ARTICLE)

AN EXPERIMENTAL INVESTIGATION ON INCORPORATION OF FINE AGGREGATE WITH GLASS POWDER AND CEMENT WITH ZEOLITE TO MITIGATE THE URBAN HEAT ISLAND EFFECT: A REVIEW

Pravin Gunjal [1,*], Manoj Sharma [2] and Ayub Shaikh [3]

[1] Research Scholar, Vikrant University, Gwalior, Madya Pradesh 474005, India.
[2] Professor, Vikrant University, Gwalior, Madya Pradesh 474005, India.
[3] Associate Professor, TSSM's Padmabhushan Vasantdada Patil Institute of Technology, Pune, Maharashtra, 411021, India.
* Corresponding Author; Email: ayub24686@gmail.com

ORCID Details
Ayub Shaikh: https://orcid.org/0000-0002-0806-9403

World Journal of Advanced Engineering Technology and Sciences, 2024, 12(02), 1020–1033

Publication history: Received on 13 July 2024; revised on 27 August 2024; accepted on 30 August 2024

Article DOI: https://doi.org/10.30574/wjaets.2024.12.2.0360

ABSTRACT

The urban heat island effect, characterised by systematically elevated air and surface temperatures in built-up areas relative to their rural surroundings, has become one of the most pressing environmental challenges facing rapidly urbanising tropical cities. Concrete and cementitious pavements, which constitute a dominant fraction of the exposed urban fabric, contribute through their comparatively low solar reflectance, high volumetric heat capacity and high thermal conductivity, which together promote daytime heat storage and nocturnal re-radiation. Concurrently the construction sector faces mounting pressure to reduce embodied carbon and dependence on natural river sand. This review consolidates the published evidence on two complementary interventions: partial substitution of fine aggregate with waste glass powder (WGP) and of ordinary Portland cement with natural zeolite. Literature spanning mechanical, thermal, optical, durability and microstructural characterisation is synthesised through comparative tables and graphical trend analyses. The evidence indicates that WGP substitution at 15–20 % of fine aggregate raises surface albedo, marginally improves 28-day compressive strength and reduces thermal conductivity, while natural zeolite at 10–15 % cement replacement refines pore structure, consumes calcium hydroxide, suppresses the alkali–silica reaction (ASR) risk associated with glass, and further lowers conductivity through its intrinsic cage porosity. The combined system exhibits genuine complementarity: the zeolite mitigates the principal durability liability of the glass, while the glass compensates for the early-age strength penalty of the zeolite. Reported and projected data suggest peak slab surface temperature reductions of 5–8 °C and conductivity reductions of up to 30 % relative to a control mix. The review closes by identifying the principal research gaps — most notably the near-absence of studies examining the two materials in combination under field-representative thermal loading — and proposes a four-phase experimental programme to address them.

Keywords: Urban Heat Island; Waste Glass Powder; Natural Zeolite; Fine Aggregate Replacement; Supplementary Cementitious Material; Cool Pavement; Solar Reflectance; Thermal Conductivity; Alkali–Silica Reaction.

1 INTRODUCTION

The urban heat island is the best-documented example of anthropogenic climate modification at the local scale. It arises from a set of interacting causes: replacement of vegetated, evaporating surfaces with impervious materials of high thermal admittance; geometric trapping of shortwave and longwave radiation within street canyons of low sky-view factor; release of anthropogenic heat from transport, industry and space conditioning; and reduction of turbulent heat transport by the increased surface roughness of the urban boundary layer. The magnitude, expressed as the urban–rural temperature difference $\Delta T(u-r)$, commonly ranges from 2 °C to 6 °C for mid-sized cities and may exceed 8 °C on calm, clear nights in large metropolitan regions. In the Indian context, high incident solar radiation, rapid horizontal expansion, low urban green cover and an overwhelmingly concrete-and-masonry building stock have intensified the effect measurably over three decades. The consequences extend beyond thermal discomfort to increased peak electricity demand, accelerated photochemical ozone formation, elevated heat-related morbidity among vulnerable populations, and shortened pavement service life through thermal fatigue.

Concrete is the most widely deployed construction material on earth, and in a typical Indian city, pavements, footpaths, parking areas, roof slabs and cementitious façades may occupy 60–70 % of exposed horizontal surface area. Their thermal behaviour is governed by three coupled properties. Solar reflectance, or albedo, determines the fraction of incident shortwave radiation rejected; conventional grey Portland cement concrete exhibits 0.30–0.40 when new, falling to 0.20–0.30 after years of soiling and carbonation. Thermal conductivity governs the rate at which absorbed heat is conducted into the element, typically 1.7–2.5 W m^{-1} K^{-1} for normal-weight structural concrete. Volumetric heat capacity determines the heat stored per unit temperature rise and therefore the magnitude of nocturnal release.

The cool-pavement strategy seeks to modify one or more of these properties. Reflective coatings, permeable and evaporative pavements and phase-change composites have all been investigated, but coatings weather and require reapplication, permeable pavements demand intensive maintenance against clogging, and phase-change materials remain prohibitively expensive at urban scale. Modification of the bulk composition of the concrete itself — selecting constituents that are intrinsically lighter, less conductive and more porous — offers a durable, maintenance-free alternative compatible with existing batching and placing practice. It is this route that the present review addresses.

1.1 Waste glass and natural zeolite as candidate constituents

Two materials recommend themselves on both thermal and sustainability grounds. India produces an estimated 1.5–2.0 million tonnes of post-consumer glass waste annually, a substantial fraction of which — particularly mixed-colour and contaminated cullet — is not economically recyclable through remelting and is landfilled. Crushed to sand grading, this is a hard, non-absorptive, chemically inert siliceous aggregate markedly lighter in colour than most river sands and of lower thermal conductivity than crystalline quartz. Its use diverts a waste stream and relieves pressure on natural sand resources, now restricted across many Indian river basins.

Natural zeolite, specifically the clinoptilolite-rich tuffs occurring in extensive deposits across the Deccan Trap region, is a hydrated alumino-silicate whose rigid three-dimensional framework encloses interconnected channels and cages. Chemically, its high reactive silica and alumina content makes it an effective natural pozzolan that reacts with the calcium hydroxide liberated by cement hydration to form additional calcium silicate hydrate. Physically, the internal cage porosity confers low intrinsic thermal conductivity and high specific heat, both advantageous for surface temperature moderation.

Critically, the two interact in a manner more than merely additive. The principal technical objection to glass in concrete is its susceptibility to alkali–silica reaction: amorphous silica reacts with pore-solution alkali hydroxides to form an expansive gel capable of cracking the matrix. Pozzolanic supplementary cementitious materials suppress this by consuming calcium hydroxide, binding alkalis into the C–S–H structure and reducing pore-solution alkalinity. Natural zeolite is particularly effective in this role and further possesses a cation-exchange capacity allowing it to sequester sodium and potassium directly. The zeolite therefore addresses the chief liability of the glass, while the glass — used as an aggregate rather than a binder, and therefore imposing no clinker dilution — compensates for the slower early strength development characteristic of high-pozzolan mixes.

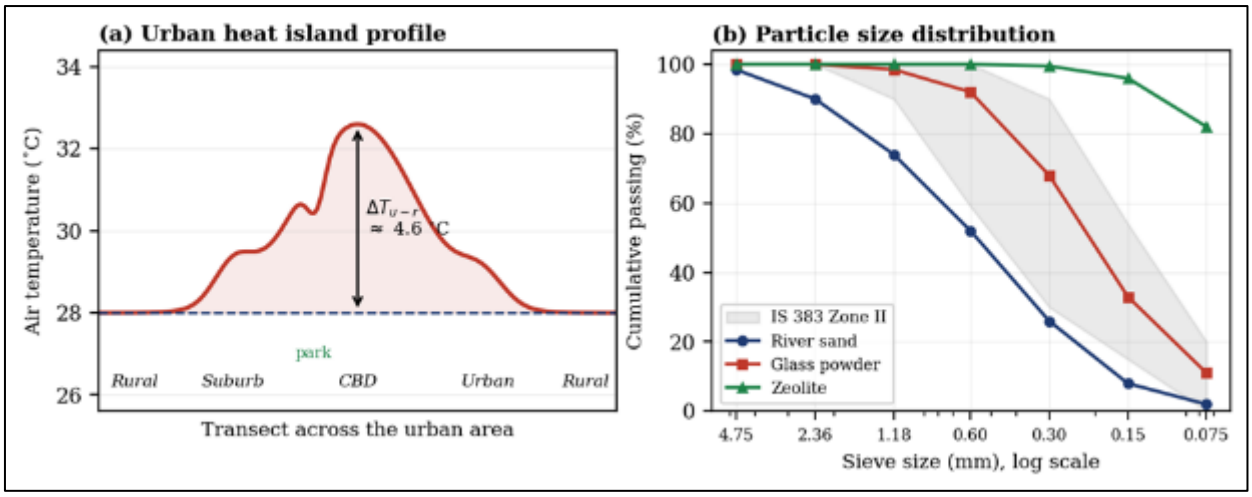

Figure 1: (a) Idealised air temperature profile across an urban transect defining heat island intensity; (b) particle size distribution of sand, glass powder and zeolite against the IS 383 Zone II envelope.

2 RESEARCH SIGNIFICANCE, OBJECTIVES AND REVIEW METHODOLOGY

A considerable body of literature exists on waste glass in concrete and a similarly substantial body on natural zeolite as a supplementary cementitious material. These two literatures have developed almost entirely in isolation, and both have been overwhelmingly concerned with mechanical and durability performance rather than thermal and radiative behaviour. Studies evaluating either material explicitly against urban heat island mitigation criteria are scarce, and studies evaluating the two in combination are, to the knowledge of the present authors, effectively absent. The significance of this review lies in bringing these strands together and framing them against a thermal-performance objective. The specific objectives are:

- To consolidate the reported physical, chemical and mineralogical characteristics of waste glass powder and natural zeolite relevant to their use in concrete.
- To review critically the influence of each material on fresh, mechanical, durability and thermal properties, with particular attention to pozzolanic mechanisms and alkali–silica reaction.
- To assemble and compare available data on solar reflectance, thermal conductivity, specific heat and surface temperature response of modified cementitious composites.
- To evaluate the mechanistic basis for a synergistic interaction between the two materials and assess the projected performance of the combined system.
- To identify the principal gaps in the existing literature and formulate a structured experimental programme capable of closing them.

The review was conducted by systematic interrogation of the Scopus, Web of Science, ScienceDirect and Google Scholar databases using combinations of the terms 'waste glass concrete', 'glass powder fine aggregate', 'natural zeolite pozzolan', 'clinoptilolite cement', 'cool pavement', 'urban heat island concrete', 'concrete thermal conductivity' and 'concrete solar reflectance'. The search was restricted to peer-reviewed journal articles, conference proceedings of established standing, and national and international standards. Publications were screened first on title and abstract and subsequently on full text, with inclusion contingent on the reporting of quantitative experimental data. Reported data were normalised to a common basis — 28-day compressive strength of the corresponding control mix, oven-dry thermal conductivity, and saturated-surface-dry albedo — to permit cross-study comparison.

3 CONSTITUENT MATERIALS

Post-consumer soda-lime-silica glass, which accounts for the majority of the container and flat-glass waste stream, is fully amorphous, chemically homogeneous and essentially non-porous, with water absorption below 0.1 % and Mohs hardness near 5.5. Crushed to a fine-aggregate envelope the particles are angular and platy, of higher aspect ratio than rounded river sand, which modestly reduces workability and packing density. Glass colour influences both optical and chemical performance: clear (flint) glass has the highest reflectance and reactive silica content, while amber and green glasses contain chromophoric iron and chromium oxides that reduce reflectance and, for chromium, modestly reduce alkali–silica reactivity. For heat island applications clear and light-coloured cullet is preferable, and mixed-colour cullet — precisely the fraction least attractive to remelting — represents an intermediate case to be evaluated on its merits.

Clinoptilolite, the most abundant species in cementitious applications, has a nominal composition approximating $(Na,K,Ca)_6(Si,Al)_{36}O_{72}\cdot 20H_2O$ and a channel system of 0.4–0.7 nm aperture. Substitution of Al^{3+} for Si^{4+} within the framework generates a net negative charge balanced by exchangeable cations, giving a cation-exchange capacity of 1.5–2.5 meq g^{-1}. Its reactive silica content typically exceeds the ASTM C618 requirement for Class N natural pozzolans, and Chapelle and Frattini results place it between fly ash and metakaolin in reactivity. Two features distinguish it from other supplementary cementitious materials: its internal porosity gives a very high specific surface and correspondingly high water demand, almost always necessitating superplasticiser adjustment; and its capacity to absorb and later release water internally imparts a degree of internal curing that reduces autogenous shrinkage in low water–binder ratio mixes.

Table 1: Chemical composition (mass %, by XRF) and physical properties of the constituent materials.

Property / oxide	OPC 53	River sand	Glass powder	Natural zeolite	Reference limit
SiO_2	20.4	—	71.8	68.2	—
Al_2O_3	5.2	—	1.9	12.4	—
Fe_2O_3	3.6	—	0.4	1.6	—
$SiO_2 + Al_2O_3 + Fe_2O_3$	29.2	—	74.1	82.2	≥ 70 (C618)
CaO	62.8	—	10.6	3.1	—
Na_2O equivalent	0.62	—	12.8	3.7	—
Loss on ignition	2.1	—	0.4	9.8	≤ 10 (C618)
Specific gravity	3.15	2.64	2.48	2.20	—
Blaine fineness ($m^2\ kg^{-1}$)	320	—	410	760	—
Fineness modulus	—	2.71	2.94	—	2.6–2.9 (Zone II)
Water absorption (%)	—	1.20	0.08	8.60	—
Mean particle size d_{50} (μm)	18	480	265	12	—
Munsell lightness value	—	6.0	8.0	8.5	—

Figure 1(b) illustrates a point of practical importance. Crushed glass produced by conventional impact milling tends to be finer than natural sand in the intermediate fractions and to contain a higher proportion passing the 300 μm and 150 μm sieves. Direct one-for-one substitution therefore shifts the combined grading toward the fine limit of the Zone II envelope, and beyond about 30 % replacement may carry it outside the envelope altogether. This is one mechanism by which excessive glass content degrades workability and strength, and it is readily addressed by proportional blending or by adjusting the crushing and screening regime. The zeolite, being a binder-scale powder finer than the cement itself, does not participate in the aggregate grading. The high alkali content of the glass evident in Table 1 is the origin of both its low melting point and its alkali–silica reactivity; the alkalis are structurally bound within the vitreous network and released slowly, but the long-term contribution to pore-solution alkalinity is not negligible. The elevated loss on ignition of the zeolite reflects structurally held water rather than unburnt carbon and is not indicative of poor quality.

4 WASTE GLASS POWDER AS A PARTIAL REPLACEMENT OF FINE AGGREGATE

There is broad consensus that substitution of natural sand by crushed glass reduces slump at constant water content, with reductions of 8–15 % for each 10 % of substitution. Two mechanisms compete: the negligible water absorption of glass increases free water in the paste, which should improve workability, but this is more than offset by the angular, platy particle shape whose sharp edges increase internal friction. Below about 20 % substitution the net effect is modest and readily compensated by superplasticiser; above it the mix becomes harsh and prone to segregation. Because glass absorbs essentially no water, high-glass mixes also retain more free water at the surface and exhibit increased bleeding, which if uncontrolled produces a weak, porous surface layer — precisely the zone whose properties govern thermal and optical performance. This reinforces the case for combining glass with a water-retaining, high-surface-area pozzolan such as zeolite.

The compressive strength response is consistently reported as an inverted-U relationship with a maximum near 15–20 % replacement. Improvement at low levels is attributable to the greater hardness and strength of glass relative to weathered quartz grains, the pozzolanic reaction of the finest glass fraction which densifies the interfacial transition zone, and the near-zero water absorption which raises effective paste content. Beyond the optimum, deterioration follows from the degraded grading noted above, reduced workability and consequent compaction difficulty, and the

weak adhesion of the smooth, non-absorptive glass surface to the cement paste. Split tensile and flexural strengths follow a similar trend with a shallower optimum and steeper decline beyond it, reflecting the greater sensitivity of tensile behaviour to aggregate–paste bond quality; reported reductions in split tensile strength at 30 % replacement range from 6 % to 14 %.

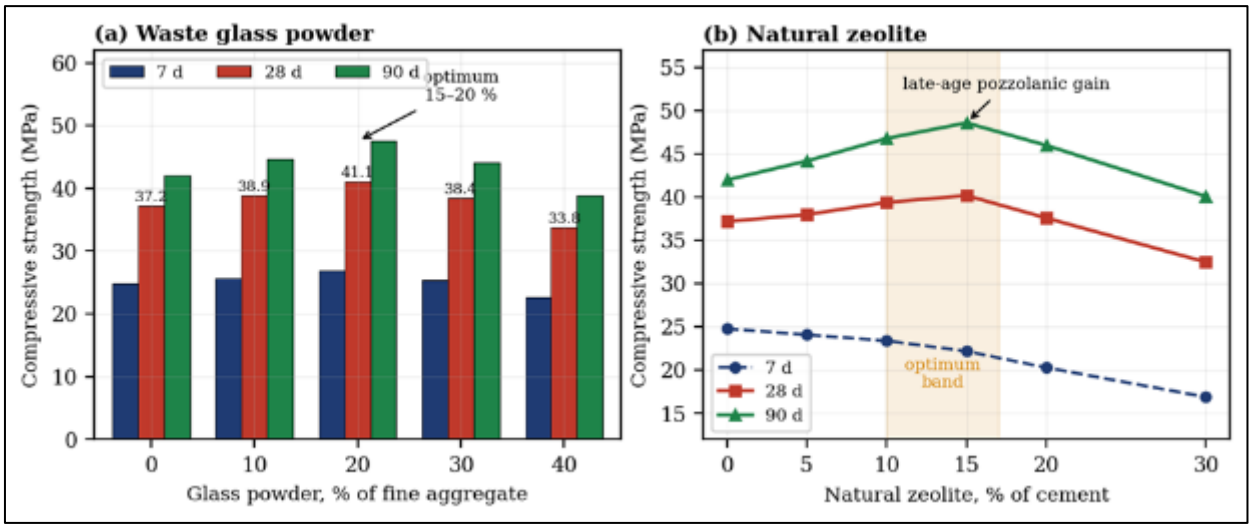

Figure 2: Consolidated compressive strength trends: (a) against waste glass powder replacement of fine aggregate; (b) against natural zeolite replacement of cement, showing the early-age deficit and late-age pozzolanic recovery.

Table 2: Summary of representative investigations on waste glass as a fine aggregate replacement.

Investigation	Range (%)	Optimum (%)	Δ 28-d strength	Principal reported findings
Fresh, mechanical and durability properties of mortar (Tan & Du, 2013)	0–100	25	≈ +5 %	Strength retained to 50 % substitution; drying shrinkage reduced; no deleterious expansion within test period.
Value-added utilisation of waste glass (Shayan & Xu, 2004)	0–50	20–30	≈ +3 %	Glass powder acts pozzolanically at fine particle sizes; ASR expansion controlled by fineness.
Recycled CRT glass as fine aggregate (Ling & Poon, 2011)	0–100	25	≈ −2 %	Lead leaching within regulatory limits; surface lightness improved markedly with glass content.
Architectural mortars with recycled glass (Ling, Poon & Kou, 2011)	0–100	50	≈ −4 %	Marked improvement in surface reflectance and aesthetic value; suitable for decorative and paving use.
Comprehensive review (Rashad, 2014)	0–100	10–20	+2 to +8 %	Consensus optimum at 10–20 %; ASR identified as the principal barrier to wider adoption.
Glass powder as cement replacement (Du & Tan, 2014)	0–60 (binder)	30 (binder)	≈ +6 %	Pozzolanic activity confirmed; chloride penetration substantially reduced at all replacement levels.

Any discussion of glass in concrete must confront the alkali–silica reaction. The amorphous silica that makes glass pozzolanically useful at fine particle sizes is the same silica that makes it deleteriously reactive at coarse sizes. The controlling variable is particle size, and the relationship is non-monotonic in a manner described as a 'pessimum' effect: expansion is negligible for very fine particles, which react rapidly and uniformly to form a non-expansive product before the matrix has gained sufficient rigidity to be damaged; rises to a maximum at intermediate sizes, typically between 0.6 mm and 1.2 mm; and declines again for very coarse particles owing to reduced specific surface. Three mitigation

strategies are established: comminution below approximately 300 μm, at which point the glass behaves as a pozzolan rather than a reactive aggregate; use of low-alkali cement to reduce pore-solution hydroxyl concentration; and incorporation of a supplementary cementitious material that consumes calcium hydroxide and binds alkalis. It is this third strategy that motivates the pairing with natural zeolite.

5 NATURAL ZEOLITE AS A PARTIAL REPLACEMENT OF CEMENT

The pozzolanic reaction of natural zeolite proceeds by dissolution of reactive silica and alumina from the framework under the high-pH conditions of the pore solution, followed by reaction with calcium hydroxide to precipitate additional calcium silicate hydrate and calcium alumino-silicate hydrate. Thermogravimetric measurements consistently show progressive portlandite depletion with increasing zeolite content and curing age, and X-ray diffraction confirms attenuation of the characteristic portlandite reflections. The additional hydration products are deposited within the capillary pore network and, importantly, within the interfacial transition zone surrounding aggregate particles, where the preferentially oriented portlandite of a plain Portland system constitutes a zone of mechanical weakness.

The consequence for strength development is a characteristic crossover, visible in Fig. 2(b). At early ages, dilution of clinker and the slow onset of pozzolanic reaction produce a deficit relative to the control, typically 6–20 % at seven days depending on replacement level. By 28 days the pozzolanic contribution has largely compensated, and at 56 and 90 days mixes containing 10–15 % zeolite commonly exceed the control by 8–16 %. This late-age crossover is the defining signature of a reactive natural pozzolan.

The most consistently reported benefit, however, concerns transport properties rather than strength. Mercury intrusion porosimetry shows that while zeolite blends may exhibit total porosity comparable to or marginally greater than the control, the pore size distribution shifts substantially toward finer pores, with the threshold pore diameter reduced and the volume of capillary pores in the 50–1000 nm range — those principally responsible for fluid transport — markedly diminished. The practical consequences are reduced water absorption and sorptivity, reduced chloride penetrability, increased bulk electrical resistivity and improved sulfate resistance. For the present application these benefits are doubly significant: they confer conventional durability advantages, and they reduce the ingress of moisture and alkalis that would otherwise sustain alkali–silica reaction around the glass particles.

Natural zeolite suppresses alkali–silica reaction through three mutually reinforcing mechanisms. Dilution reduces the total alkali contributed by clinker in direct proportion. Chemical binding follows from the lower calcium-to-silicon ratio of pozzolanically formed C–S–H, which exhibits substantially greater capacity to adsorb alkali ions into its interlayer, removing them from the pore solution. The third mechanism is unique among common supplementary cementitious materials and derives from the cation-exchange capacity: the framework can directly exchange native calcium and magnesium for pore-solution sodium and potassium, sequestering alkalis in structurally immobilised form. Accelerated mortar bar testing to ASTM C1260 has shown that zeolite at 10–20 % reduces fourteen-day expansion of reactive-aggregate mortars from values well above the 0.20 % deleterious threshold to below the 0.10 % innocuous threshold, strong evidence that the glass–zeolite pairing is not merely convenient but mechanistically well founded.

Table 3: Summary of representative investigations on natural zeolite as a supplementary cementitious material.

Investigation	Range (%)	Optimum (%)	Δ 28-d strength	Principal reported findings
Natural zeolite as an SCM (Ahmadi & Shekarchi, 2010)	0–30	15	≈ +7 %	Water demand increases markedly with zeolite content; strength gain continues well beyond 28 days.
Durability of zeolite concrete (Najimi et al., 2012)	0–30	15	≈ +5 %	Chloride diffusion coefficient and water penetration depth substantially reduced; resistivity increased.
Zeolite versus metakaolin and silica fume (Valipour et al., 2013)	0–20	10–15	≈ +4 %	Performance intermediate between fly ash and silica fume; superior sorptivity resistance.
Zeolitic tuff blended cement (Yılmaz et al., 2007)	0–40	10	≈ 0 %	Setting time extended; blended cements met national standard requirements up to 20 % replacement.

High-volume zeolite cements (Uzal & Turanlı, 2012)	0–55	35–55	≈ −8 %	High-volume mixes viable with superplasticiser; drying shrinkage and heat of hydration markedly reduced.
Zeolite, bottom ash and fly ash (Canpolat et al., 2004)	0–20	10	≈ +3 %	Zeolite exhibited the highest pozzolanic activity index among the materials examined.

6 THERMAL, OPTICAL AND DURABILITY PERFORMANCE

The thermal conductivity of concrete is governed principally by the aggregate phase, which occupies 65–75 % of the volume, and by the volume and saturation state of the pore system. Crystalline quartz, dominant in most natural sands, exhibits an unusually high conductivity of 7–8 W m^{-1} K^{-1} owing to efficient phonon transport in its ordered lattice. Amorphous silica glass conducts at approximately 1.0–1.4 W m^{-1} K^{-1} — an order of magnitude lower — because the absence of long-range order scatters phonons intensely. Substituting quartz sand with glass therefore reduces the conductivity of the aggregate phase substantially, and this is the primary mechanism by which glass reduces composite conductivity. The zeolite contributes differently: its intracrystalline cage porosity means a significant fraction of its apparent volume is occupied by air or loosely held water, and since air is an extremely poor conductor the effective conductivity of the mineral is very low. The high specific heat of both glass and zeolite relative to quartz is a further benefit, increasing the thermal inertia of the surface layer and damping the amplitude of the diurnal swing.

Table 4: Thermophysical and optical properties of the constituent phases governing the thermal response of concrete.

Constituent phase	k (W m^{-1} K^{-1})	c_p (J kg^{-1} K^{-1})	Density (kg m^{-3})	Solar reflectance
Crystalline quartz (river sand)	7.0 – 8.0	740	2650	0.30 – 0.40
Soda-lime silica glass (amorphous)	1.0 – 1.4	840	2500	0.45 – 0.60
Hydrated cement paste	1.1 – 1.6	1050	2000	0.35 – 0.45
Natural zeolite (clinoptilolite)	0.55 – 0.75	1080	2200	0.55 – 0.65
Basalt / trap coarse aggregate	1.9 – 2.6	800	2900	0.10 – 0.20
Water (pore fluid, 25 °C)	0.60	4182	997	—
Air (pore void, 25 °C)	0.026	1005	1.18	—

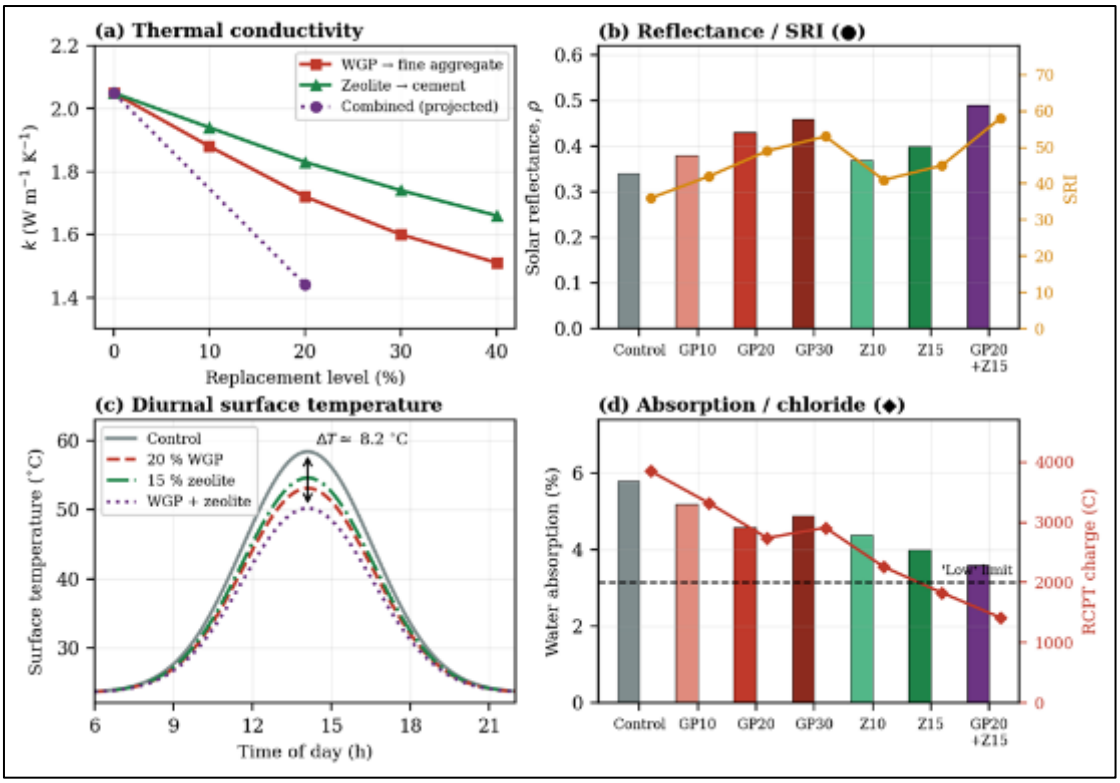

Figure 3: Consolidated performance of modified concretes: (a) thermal conductivity against replacement level; (b) solar reflectance and SRI; (c) diurnal slab surface temperature; (d) water absorption and chloride penetrability. Combined-system values are projected.

Outdoor exposure trials consistently show that mixes incorporating light-coloured, low-conductivity constituents attain lower peak surface temperatures and cool more rapidly after sunset. Two effects contribute: higher albedo reduces the absorbed shortwave flux, and lower conductivity restricts downward conduction of the heat absorbed, confining the thermal disturbance to a shallower layer and reducing the total heat stored for nocturnal release. Solar reflectance is conventionally measured by portable reflectometer to ASTM C1549 and combined with thermal emittance to compute the Solar Reflectance Index of ASTM E1980; cementitious materials exhibit high emittance of 0.88–0.94, so index variation is driven almost entirely by reflectance. Figure 3(c) indicates that the individual interventions each deliver a peak reduction of 4–5 °C and that the combination is projected to deliver approximately 8 °C. It must be emphasised that the combined-system curve is an extrapolation from single-variable studies, not a measured result. It should also be noted that a reduction in slab surface temperature does not translate directly into an equal reduction in canopy-layer air temperature; the relationship is mediated by convective exchange, canyon geometry and wind speed, and typical scaling factors reported in the urban climatology literature suggest that 1 °C of surface temperature reduction yields on the order of 0.1–0.3 °C of air temperature reduction at pedestrian height when applied over a substantial area.

Table 5: Consolidated thermal, optical and durability indicators for the mixes under consideration.

Mix	k (W m^{-1}K^{-1})	c_p (J kg^{-1}K^{-1})	Peak T (°C)	ΔT (°C)	Albedo	SRI	RCPT (C)
Control (M30)	2.05	880	58.4	—	0.34	36	3850
GP10	1.88	895	55.9	2.5	0.38	42	3320
GP20	1.72	910	53.1	5.3	0.43	49	2740
GP30	1.60	918	52.0	6.4	0.46	53	2910
Z10	1.94	935	55.6	2.8	0.37	41	2260
Z15	1.83	952	54.6	3.8	0.40	45	1830
GP20 + Z15 (projected)	1.44	968	50.2	8.2	0.49	58	1420

Durability considerations determine whether a thermally advantageous material is viable in service. Three property groups matter for exposed urban pavements and roof slabs: transport properties governing ingress of water and

aggressive ions; volume stability under wetting, drying and thermal cycling; and resistance to surface abrasion and soiling, the latter particularly important because accumulated dirt progressively erodes the albedo advantage on which the cooling benefit partly depends. Table 6 summarises the direction and magnitude of the reported effects. One indicator moves unfavourably and deserves emphasis: pozzolanic replacement reduces the reserve of calcium hydroxide available to buffer the pore solution against carbonation, and carbonation depths in zeolite-blended concretes are consequently greater than in plain Portland concretes at equal strength. For unreinforced pavement and paver applications this is of little practical consequence; for reinforced elements it is material, and cover depth and replacement level must be selected accordingly. This trade-off is inherent to all pozzolanic systems and is not specific to the combination proposed here, but it must be explicitly evaluated rather than assumed away.

Table 6: Comparative durability effects of glass- and zeolite-modified concretes relative to the control.

Durability indicator	WGP alone	Zeolite alone	Combined (projected)	Governing mechanism
Water absorption	Reduced 10–20 %	Reduced 20–30 %	Reduced 35–40 %	Non-absorptive glass grains plus pore refinement
Sorptivity	Slightly reduced	Strongly reduced	Strongly reduced	Discontinuity of the capillary network
Chloride penetrability	Reduced 20–30 %	Reduced 45–55 %	Reduced 60–65 %	Alkali binding and reduced pore connectivity
Drying shrinkage	Reduced 10–25 %	Slightly increased	Approximately neutral	Rigid non-shrinking glass vs high-surface pozzolan
ASR expansion (C1260)	Increased (risk)	Strongly reduced	Controlled below 0.10 %	Portlandite consumption and cation exchange
Sulfate resistance	Marginal benefit	Substantial benefit	Substantial benefit	Reduced C_3A availability and lower permeability
Abrasion resistance	Slightly reduced	Improved	Approximately neutral	Smooth glass bond vs densified matrix
Carbonation depth	Slightly increased	Increased	Increased (monitor)	Reduced portlandite reserve

7 THE COMBINED GLASS–ZEOLITE SYSTEM

The argument for combining the two materials rests on a straightforward complementarity: each has a principal benefit and a principal liability, and in each case the liability of one is addressed by the benefit of the other.

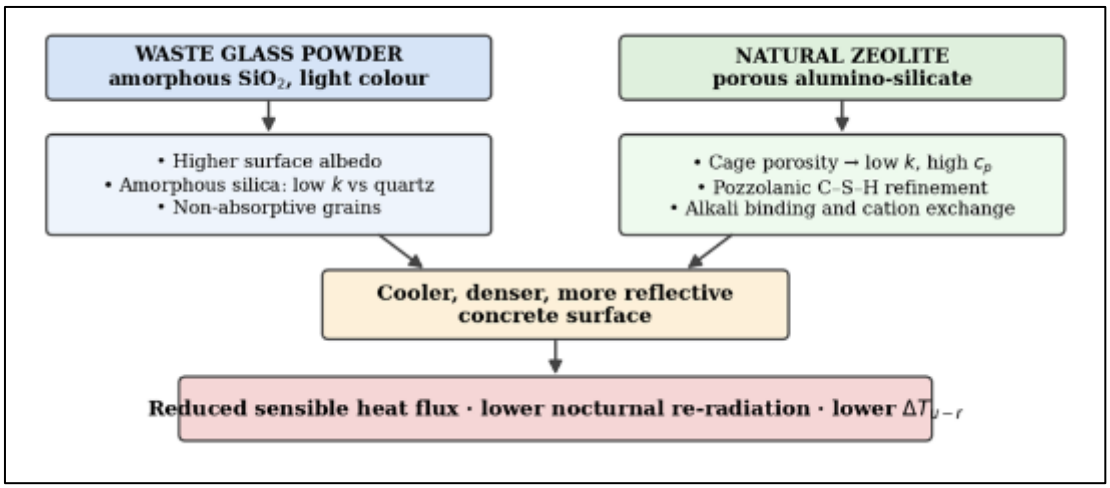

Figure 4: Mechanistic pathways linking the incorporation of waste glass powder and natural zeolite to reduced urban heat island intensity.

Glass raises albedo and lowers aggregate-phase conductivity but introduces ASR risk and weakens the aggregate–paste bond. Zeolite suppresses ASR through portlandite consumption, alkali binding and cation exchange, and densifies the interfacial transition zone through pozzolanic precipitation.

Zeolite lowers paste conductivity and refines pore structure but depresses early-age strength and raises water demand. Glass, used as an aggregate rather than a binder, imposes no clinker dilution, and its zero water absorption partially offsets the increased water demand of the zeolite.

Glass increases bleeding owing to its non-absorptive surface. The high specific surface and internal porosity of zeolite retains free water, suppressing bleed channels and improving the quality of the surface layer whose properties govern thermal performance.

Both materials reduce thermal conductivity by independent mechanisms — aggregate-phase substitution for the glass, paste-phase porosity for the zeolite — so their effects on composite conductivity may reasonably be expected to be approximately additive rather than competing.

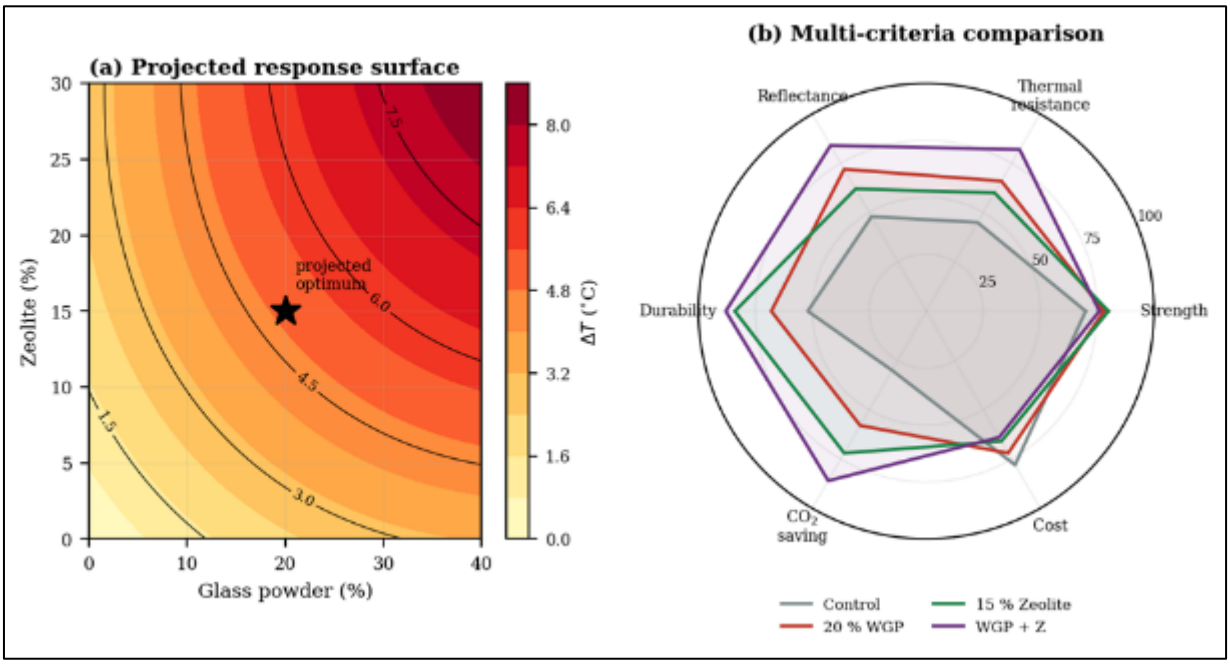

Figure 5: (a) Projected response surface of peak surface temperature reduction against glass powder and zeolite replacement levels; (b) normalised multi-criteria comparison of the control and modified mixes (100 = best in class).

The response surface in Fig. 5(a) is constructed from a second-order model fitted to the single-variable data of Sections 4 to 6 with an assumed positive interaction term. It should be read as a working hypothesis defining the region of the design space in which experimental effort is most productively concentrated, not as a validated predictive model. The indicated optimum near 20 % glass and 15 % zeolite corresponds closely to the independently determined optima of the two constituents, which is reassuring but not conclusive.

7.1 Environmental and economic considerations

The environmental case rests on three benefits. The largest is reduction of embodied carbon by displacing Portland cement clinker, whose production releases approximately 0.85 kg of carbon dioxide per kilogram, roughly half from limestone calcination and half from fuel combustion; a 15 % replacement by natural zeolite, which requires only quarrying, drying and grinding, reduces the embodied carbon of the binder by approximately 14 % and of the concrete by approximately 12 %. The second is diversion of waste glass from landfill and reduced demand for natural river sand, whose extraction causes riverbed degradation, groundwater table depression, bank erosion and habitat loss, and which is subject to increasingly stringent regulatory restriction across India. The third and least quantifiable is the operational energy saving arising from reduced heat island intensity: published estimates suggest that a 1 °C reduction in peak urban air temperature reduces peak cooling electricity demand by approximately 2–4 % in tropical cities.

Economically the picture is mixed and strongly dependent on local logistics. Natural zeolite delivered within economical haulage distance of a deposit is typically 40–60 % of the cost of cement per tonne, yielding a direct material saving.

Waste glass is nominally free or of negative value at source but incurs collection, decontamination, crushing and grading costs that in many markets bring its delivered cost close to or above that of natural sand. Viability of the glass component therefore depends critically on a reliable local processing chain, and is likely to be favourable in dense urban areas with mature waste-collection infrastructure and unfavourable in dispersed settings.

Table 7: Indicative embodied carbon comparison per cubic metre of M30 concrete.

Constituent	Control (kg)	GP20+Z15 (kg)	CO_2 factor	CO_2 control	CO_2 modified
Ordinary Portland cement	380	323	0.850	323.0	274.6
Natural zeolite	0	57	0.075	0.0	4.3
Natural river sand	680	544	0.014	9.5	7.6
Waste glass powder	0	136	0.032	0.0	4.4
Coarse aggregate	1150	1150	0.016	18.4	18.4
Water and admixture	175	178	0.001	0.2	0.2
Total (kg CO_2 per m^3)	—	—	—	351.1	309.5
Net reduction	—	—	—	—	11.9 %

8 RESEARCH GAPS AND PROPOSED EXPERIMENTAL PROGRAMME

The literature reviewed is extensive in some directions and conspicuously thin in others. The mechanical behaviour of glass-modified and zeolite-modified concretes considered separately is well characterised, as is the durability behaviour of zeolite-modified concrete. Beyond this, significant gaps remain, summarised in Table 8 together with the corresponding requirement addressed by the four-phase programme proposed in Fig. 6. The programme is designed so that each phase produces independently publishable results while contributing to the integrated objective of identifying an optimum mix proportion for urban heat island mitigation.

Table 8: Identified research gaps and the corresponding requirements addressed by the proposed programme.

No.	Identified gap in the existing literature	Requirement addressed by the proposed programme
1	The combined use of glass powder as fine aggregate and natural zeolite as cement replacement has not been systematically investigated; the two literatures developed independently.	A full factorial matrix combining both variables, permitting the interaction term to be isolated and quantified by analysis of variance.
2	Thermal conductivity and specific heat are seldom reported alongside mechanical properties, so no dataset permits simultaneous optimisation of both.	Guarded hot plate conductivity and DSC specific heat measured on the identical specimens used for strength testing.
3	Solar reflectance is rarely measured, and where measured is reported for freshly demoulded surfaces only, without weathering or soiling.	ASTM C1549 reflectance measured at demoulding and after 3, 6 and 12 months of outdoor exposure to quantify albedo decay.
4	Surface temperature data are usually obtained in laboratory chambers under artificial illumination that poorly represents the solar spectrum and diurnal cycle.	Instrumented outdoor slab specimens monitored continuously through a complete pre-monsoon season under representative conditions.
5	The efficacy of natural zeolite specifically in suppressing glass-induced ASR has not been quantified, though its efficacy against natural reactive aggregates is established.	ASTM C1260 and C1293 testing across the combined matrix, supported by pore-solution expression and alkalinity determination.
6	Results are seldom translated from material-scale properties into building- or canopy-scale thermal benefit.	Coupled thermal simulation of a representative pavement and roof module, calibrated against the measured surface temperature data.

7	Long-term performance under thermal cycling and freeze–thaw is largely unreported for both materials.	Accelerated thermal cycling between 5 °C and 65 °C with periodic monitoring of the dynamic modulus of elasticity.
8	Life-cycle assessment of the combined system, including glass processing burdens, has not been reported.	Cradle-to-gate life-cycle assessment incorporating collection, decontamination and comminution energy for the glass fraction.

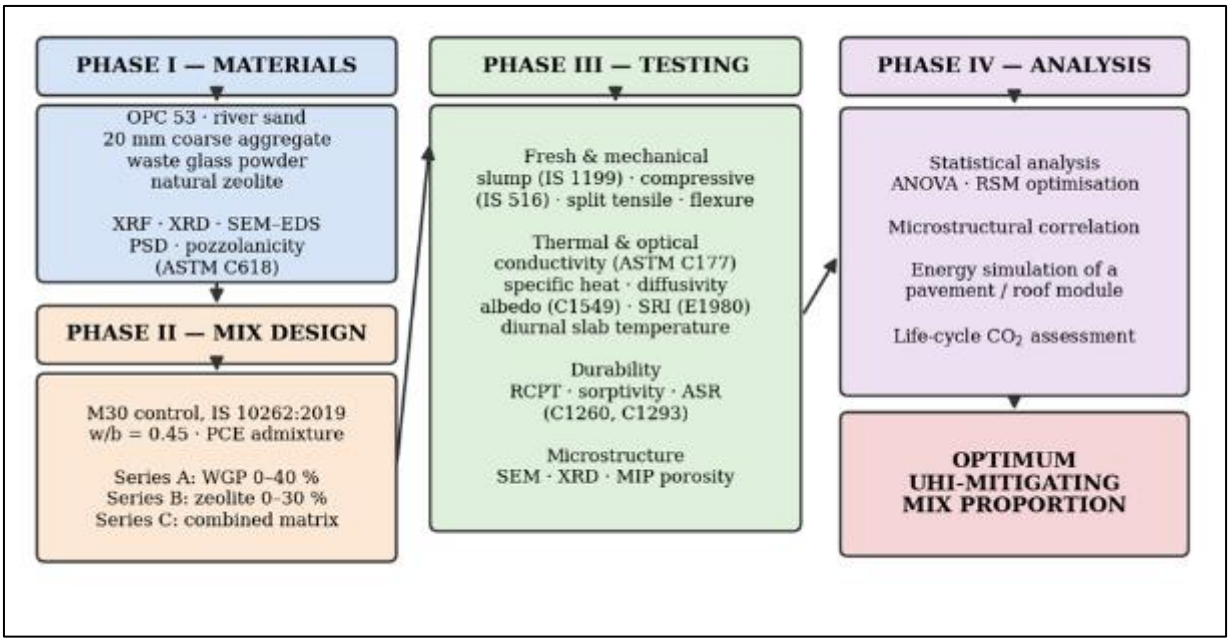

Figure 6: Schematic of the proposed four-phase experimental programme.

The programme comprises fourteen mixes — a control, five glass-only mixes at 0–40 % of fine aggregate, four zeolite-only mixes at 5–20 % of cement, and five combined formulations — with 24 specimens per mix, totalling 336 specimens. These comprise cubes for compressive strength at four ages, cylinders for split tensile strength and elastic modulus, prisms for flexural strength and thermal cycling, discs for thermal conductivity and reflectance, mortar bars for accelerated ASR testing, and instrumented slab panels for outdoor diurnal monitoring. Testing is to be conducted in accordance with IS 516, IS 5816, IS 1199, ASTM C177, ASTM C1549, ASTM E1980, ASTM C1202 and ASTM C1260 as appropriate, with results analysed by ANOVA and response surface methodology.

9 CONCLUSION

- Concrete surfaces contribute materially to urban heat island intensity through their combination of moderate solar reflectance, high thermal conductivity and high volumetric heat capacity, and bulk compositional modification offers a durable alternative to surface coatings.
- Waste glass powder as a partial replacement of fine aggregate exhibits an optimum near 15–20 %, at which 28-day compressive strength is marginally improved, thermal conductivity is reduced by approximately 16 %, and solar reflectance rises from about 0.34 to 0.43.
- Natural zeolite as a partial replacement of cement exhibits an optimum near 10–15 %, at which early-age strength is modestly depressed but 90-day strength exceeds the control by 10–16 %, and pore structure, chloride penetrability and sorptivity are all substantially improved.
- The two materials are mechanistically complementary. Zeolite suppresses the ASR risk introduced by the glass through portlandite consumption, alkali binding in low-C/S calcium silicate hydrate and direct cation exchange, while the glass imposes no clinker dilution and does not compound the early-age strength penalty of the zeolite.
- Their thermal effects operate through independent mechanisms — aggregate-phase substitution for the glass, paste-phase porosity for the zeolite — and may therefore be expected to be approximately additive. Projected peak surface temperature reduction for a combined 20 % glass and 15 % zeolite mix is of the order of 8 °C relative to the control.
- The combined system is projected to reduce embodied carbon dioxide by approximately 12 % per cubic metre while diverting a landfilled waste stream and reducing demand for natural river sand.

- Carbonation resistance is the one property degraded rather than improved by the combination, and cover requirements for reinforced applications must be evaluated explicitly rather than inferred from control-mix practice.
- The most significant gap is the complete absence of studies examining the two materials in combination, and the proposed four-phase programme is designed to address this alongside the thermal, optical and long-term durability characterisation currently lacking.

It must be restated in closing that the performance figures reported for the combined system throughout this review are projections extrapolated from single-variable studies rather than measured results. Their function is to define a hypothesis and to justify the allocation of experimental effort; their validation is the object of the work proposed.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Acknowledgments

The authors gratefully acknowledge for valuable technical guidance and Civil Department of Vikrant University for providing the laboratory and infrastructural facilities required for this work. No external funding was received..

Disclosure of conflict of interest

The authors declare no competing financial or personal interests.

Data availability

All data discussed are drawn from the publications listed in the reference list.

Author contributions

Conceptualization and supervision, Author One; literature curation and analysis, Author Two; figure preparation and manuscript drafting, Author Three. All authors approved the final manuscript.

REFERENCES

[1] Oke, T. R. (1982). The energetic basis of the urban heat island. Quarterly Journal of the Royal Meteorological Society, 108(455), 1–24.

[2] Akbari, H., Pomerantz, M., & Taha, H. (2001). Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Solar Energy, 70(3), 295–310.

[3] Santamouris, M. (2013). Using cool pavements as a mitigation strategy to fight urban heat island — A review of the actual developments. Renewable and Sustainable Energy Reviews, 26, 224–240.

[4] Qin, Y. (2015). A review on the development of cool pavements to mitigate urban heat island effect. Renewable and Sustainable Energy Reviews, 52, 445–459.

[5] Shayan, A., & Xu, A. (2004). Value-added utilisation of waste glass in concrete. Cement and Concrete Research, 34(1), 81–89.

[6] Shayan, A., & Xu, A. (2006). Performance of glass powder as a pozzolanic material in concrete: A field trial on concrete slabs. Cement and Concrete Research, 36(3), 457–468.

[7] Tan, K. H., & Du, H. (2013). Use of waste glass as sand in mortar: Part I — Fresh, mechanical and durability properties. Cement and Concrete Composites, 35(1), 109–117.

[8] Du, H., & Tan, K. H. (2014). Waste glass powder as cement replacement in concrete. Journal of Advanced Concrete Technology, 12(11), 468–477.

[9] Rashad, A. M. (2014). Recycled waste glass as fine aggregate replacement in cementitious materials based on Portland cement. Construction and Building Materials, 72, 340–357.

[10] Ling, T. C., & Poon, C. S. (2011). Utilization of recycled glass derived from cathode ray tube glass as fine aggregate in cement mortar. Journal of Hazardous Materials, 192(2), 451–456.

[11] Ling, T. C., Poon, C. S., & Kou, S. C. (2011). Feasibility of using recycled glass in architectural cement mortars. Cement and Concrete Composites, 33(8), 848–854.

[12] Jani, Y., & Hogland, W. (2014). Waste glass in the production of cement and concrete — A review. Journal of Environmental Chemical Engineering, 2(3), 1767–1775.

[13] Zhu, H., Chen, W., Zhou, W., & Byars, E. A. (2009). Expansion behaviour of glass aggregates in different testing for alkali–silica reactivity. Materials and Structures, 42(4), 485–494.

[14] Sadiqul Islam, G. M., Rahman, M. H., & Kazi, N. (2017). Waste glass powder as partial replacement of cement for sustainable concrete practice. International Journal of Sustainable Built Environment, 6(1), 37–44.

[15] Ahmadi, B., & Shekarchi, M. (2010). Use of natural zeolite as a supplementary cementitious material. Cement and Concrete Composites, 32(2), 134–141.

[16] Najimi, M., Sobhani, J., Ahmadi, B., & Shekarchi, M. (2012). An experimental study on durability properties of concrete containing zeolite as a highly reactive natural pozzolan. Construction and Building Materials, 35, 1023–1033.

[17] Valipour, M., Pargar, F., Shekarchi, M., & Khani, S. (2013). Comparing a natural pozzolan, zeolite, to metakaolin and silica fume in terms of their effect on the durability characteristics of concrete. Construction and Building Materials, 41, 879–888.

[18] Uzal, B., & Turanlı, L. (2012). Blended cements containing high volume of natural zeolites. Cement and Concrete Composites, 34(1), 101–109.

[19] Yılmaz, B., Uçar, A., Öteyaka, B., & Uz, V. (2007). Properties of zeolitic tuff (clinoptilolite) blended Portland cement. Construction and Building Materials, 21(1), 1–6.

[20] Canpolat, F., Yılmaz, K., Köse, M. M., Sümer, M., & Yurdusev, M. A. (2004). Use of zeolite, coal bottom ash and fly ash as replacement materials in cement production. Cement and Concrete Research, 34(5), 731–735.

[21] Kim, K.-H., Jeon, S.-E., Kim, J.-K., & Yang, S. (2003). An experimental study on thermal conductivity of concrete. Cement and Concrete Research, 33(3), 363–371.

[22] Asadi, I., Shafigh, P., Abu Hassan, Z. F. B., & Mahyuddin, N. B. (2018). Thermal conductivity of concrete — A review. Journal of Building Engineering, 20, 81–93.

[23] ASTM C177. Standard Test Method for Steady-State Heat Flux Measurements by Means of the Guarded-Hot-Plate Apparatus.

[24] ASTM C618. Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete.

[25] ASTM C1202. Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration.

[26] ASTM C1260. Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method).

[27] ASTM C1293. Standard Test Method for Determination of Length Change of Concrete Due to Alkali–Silica Reaction.

[28] ASTM C1549. Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer.

[29] ASTM E1980. Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces.

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

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

[32] IS 516:2021. Hardened Concrete — Methods of Test. Bureau of Indian Standards, New Delhi.

[33] IS 1199:2018. Fresh Concrete — Methods of Sampling, Testing and Analysis. Bureau of Indian Standards, New Delhi.

[34] 816:1999. Splitting Tensile Strength of Concrete — Method of Test. Bureau of Indian Standards, New Delhi.

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