SUSTAINABLE CONCRETE DEVELOPMENT USING FLY ASH: PROSPECTS, CHALLENGES, AND CONSTRUCTION TIME EFFICIENCY

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ABSTRACT

The increased interest in environmental sustainability at a global level has hastened research and development efforts into supplementary cementitious materials (SCMs) which can be utilized as partial or full replacements for Ordinary Portland Cement (OPC) in concrete. Fly ash which is a fine particulate SCM that is a by-product of thermal power plants in which coal is burnt for generating electricity has shown a considerable ability towards green construction techniques and is among the most researched SCMs. This review paper provides a synthesis of the existing literature and meta-analytical evidencebases on the potential directions of fly ash use in concrete while exploring its technical potential sand practical challenges that have limited its adoption. The paper provides overview of fly ash classification (Class C and Class F), pozzolanic activity, workability enhancement, long-term strength, permanent durability and reduction of carbon dioxide emissions. At the same time, it will also tackle major issues such as inconsistency in the characteristics of fly ash, leachate of heavy metals, absence of a unifying regulation across jurisdictions, delayed setting, and scarcity of fly ash in some locations.

Keywords: *fly ash concrete[1], supplementary cementitious materials[2], sustainable construction[3], pozzolanic reactivity[4], carbon footprint reduction[5], heavy metal leaching[6], circular economy[7].*

1. INTRODUCTION

1.1 GLOBAL CONTEXT OF SUSTAINABLE CONSTRUCTION

The construction industry is one of the most resource-exhausting industries in the world, with the buildings sector alone making up nearly 8-10% of total anthropogenic carbon dioxide (CO2) emissions [1]. Traditional concrete is made with Ordinary Portland Cement (OPC) a binding agent that is produced by calcining limestone (CaCO3) at temperatures above 1400 degrees Celsius, emitting tons of CO2 into the air just for making it. With increasing infrastructure demand around the world especially in emerging economies across Asia, Africa, and

Latin America unless systemic alternatives are implemented at scale, it appears that the environmental footprint of cement production will also grow. The United Nations Sustainable Development Goal 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action) together highlight the need to transition the built environment to carbon neutral buildings and designs [2]. Herein, supplementary cementitious materials (SCMs) are of great interest, as they are sustainable alternatives that can replace cement partially or completely leading to reduced carbon footprint in concrete while meeting structural performance. In the context of SCMs, fly ash is one of the most plentiful, economical, and technically innovative materials in modern concrete technology. While the global annual production of fly ash is over 700 million tonnes, construction applications have exploited only a small fraction of this potential, revealing both the opportunity and urgent need for fly ash-concrete systems to be adopted as a key mainstream building material in the broader context of materials sustainability.

1.2 FLY ASH AS A CONSTRUCTION MATERIAL: AN OVERVIEW

Fly ash is a glassy, spherical powder remaining by-product from burning coal in thermal electricity-generating plants. Non-combustible inorganic minerals are also present in some pulverised fuel, and are introduced into the combustion process in a non-fuel bound form, when pulverised coal is burned at high temperatures, they melt and form fine droplets, which become fused together during cooling, solidifying as fine glass spheres, with some droplet fines carried out of the combustion chamber via exhaust gases and captured by electrostatic precipitators or bag filters [3]. Fly ash is grouped into two major categories according to the ASTM C618 classification scheme Class C (high-calcium, self-cementitious) and Class F (low-calcium, pozzolanic) with different chemical compositions and performance characteristics of concrete [5]. Class F fly ash, primarily derived from the combustion of bituminous or anthracite coal, reacts with calcium hydroxide released from cement hydration to yield additional calcium silicate hydrate (C-S-H) the main binding compound in concrete, thus enhancing lasting strength and reducing permeability [5]. Class C fly ash comes from sub-bituminous coal or lignite and has enough calcium oxide to be self-hardening without Portland cement. Fly ash used in concrete mixtures has been proven to improve workability, reduce water demand, increase sulfate resistance, alkali-silica reaction Damage (ASR) and chloride ion penetration resistance, resulting in an extended service life and a reduction in lifecycle maintenance costs [6]. The spherical particle morphology of fly ash has lubricating properties it acts as a ball-bearing lubricant within fresh concrete mixes, reducing interparticle friction and improving flowability with no increase in water which makes fly ash particularly important in self-compacting concrete formulations. Furthermore, the latent hydraulic and pozzolanic reactivity of fly ash develop heat at a rate slower than the hydration of Portland cement, lowering the maximum temperature rise in mass concrete placements thereby reducing the possibility of thermal cracking.

1.3 SCOPE AND OBJECTIVES OF THIS REVIEW

Although research on fly ash concrete is abundant and growing, full scale implementation in construction practice is hindered by various technical, regulatory and socio-economic barriers that up to now have not been evaluated systematically in a consistent meta-analytical framework. To fill that gap, the present review paper examines peer-reviewed literature published to date from 1990 to 2025, providing a synthesis of results across experimental studies, field applications, lifecycle assessments, and policy analyses. The specific objectives are: (i) to investigate the state of fly ash practices in concrete from compressive strength, durability, and sustainability perspectives, (ii) to undertake a meta-analytical assessment of pivotal performance metrics as employed in leading research, (iii) to recognize and classify the foremost challenges to fly ash adoption, (iv) to evaluate discrepancies and gaps in previous research, and (v) to suggest opportunities for future research and policy targets. The structure of the review aligns along the lines of theory evidence synthesis to enable both a theoretical base along with practical steps to advance fly ash based sustainable concrete worldwide. The scope covers structural, geotechnical and environmental engineering aspects because fly ash is utilized as both a cement replacement in structural concrete as well as in road base stabilization, embankment fill, grouting and mine reclamation, which together represent an essential part of this industrial by-product´s circular economy potential.

2. LITERATURE SURVEY

Research literature reporting potential use of fly ash in concrete dates back to the mid-twentieth century, when a few investigators observed its pozzolanic nature and potential to enhance (or better yet replace) Portland cement. Davis et al. [7] In the 1930s and 1940s laid the groundwork for the pozzolanic behavior of fly ash when mixed with lime and water and proved that fly ash could form cementitious compounds which increase the strength and durability of concrete. These groundbreaking discoveries established the foundation for decades of research gradually characterized fly ash by its mineralogical composition, particle morphology, chemical reactivity, and engineering performance in concrete mixtures of diverse design and contextual application.

An extensive amount of literature focused on the early age compressive strength development of fly ash concrete during the 1980s and 1990s. Mehta [8] reported that although (HVFA) concrete defined as a mixture containing 50 percent or more fly ash by mass of cementitious materials has slower early strength development than OPC concrete, again, proportions with low water-to-binder ratios can yield 28-day and 90-day strengths comparable to and sometimes higher than 90-day strengths for properly proportioned OPC concrete. Malhotra and Ramezanianpour [9] compiled the experimental results of different countries and showed that the normal water-to-binder ratios (0.30-0.35) with HVFA concrete (e.g., as much as 40% by mass of binder) can obtain 90-day compressive strengths over 60 MPa and thus could replace high-performance concrete in many structural applications. The pozzolanic reaction in fly ash concrete lags behind the primary hydration of cement clinker phases, which is a benefit (lower heat of hydration for mass concrete applications), but also a detriment in cold weather applications with high early strength requirements to remove forms for posttensioning and structural load scheduling. The limitation was naturally mitigated due to the targeted usage of supplementary accelerators, increased curing temperatures, or reduction of fly ash content during winter construction periods without compromising the durability benefit of using fly ash in concrete.

The durability aspects of fly ash concrete were studied intensively since the 1990s, and a consensus was reached that, in most cases, the incorporation of fly ash significantly improves the resistance of concrete to both chemical and physical deterioration mechanisms. Naik et al. Class F fly ash concrete was shown by [10] to have significantly lower chloride ion permeability measured by RCPT (ASTM C1202) than that of the control concrete, explaining this by the fact that pozzolanic reactions densify the microstructure by refining the pore structure and decreasing interconnected porosity. In a study by Thomas [11] and also in a study by Bleszynski et al. It has been demonstrated that fly ash concrete offers enhanced alkali-silica reaction (ASR) resistance by diluting the alkali content and consuming calcium hydroxide that would otherwise react to form ASR gel [12]. Data documenting substantial enhancement in sulfate service life of fly ash concrete is also widely available, with investigations performed by Torii and Kawamura [13] demonstrating that lower aluminate content in fly ash systems results in decreased production of expansive ettringite and gypsum through chemical reaction with sulfate-bearing marine soils, groundwater, and industrial effluent. Taken together, these durability improvements result in service lives for fly ash concrete infrastructure that are orders of magnitude longer, with lifecycle cost models demonstrating economic benefits that accumulate meaningfully over the 50- to 100-year design life horizons typical of bridges, tunnels, and marine structures.

Studies featuring lifecycle assessment (LCA) of the environmental and sustainability dimensions of fly ash concrete have been conducted from the 2000s on and thus are examined here in detail. Habert et al. [14] LCA methodology was employed in to quantify the reduction in global warming potential (GWP) derived from fly ash substitution, showing that the replacement of 30% of cement with fly ash decreased the embodied CO2 in the material from 20 to 25%, whereas a 50% replacement led to reductions of 35–40% in embodied CO2. Kumar et al., [15] supplemented this with thermodynamic modeling of fly ash blended systems, showing that the long-term phase assemblage, dominated by calcium silicate hydrate at low Ca/Si ratios, stratlingite, and hydrogarnet, is fundamentally diffierent from OPC systems and contributes to superior chemical stability over decades of the service. Siddique [16] viewed the resource efficiency dimension, in each tonne of fly ash used in cement or concrete avoids the landfilling of a solid waste material that contributes to landfilling pressure, and (secondly with an additional co-benefit) conserves naturally occurring raw materials such as limestone, clay and silica (for cement production) which otherwise risk being quarried. This not only diverts waste but it also conserves valuable raw materials, making fly ash one of the most materially efficient SCMs, especially from the perspective of circular economy.

The mechanical properties of fly ash concrete have also been investigated in terms of tensile strength, flexural strength, elastic modulus, and shrinkage behavior. Bouzoubaa and Lachemi [17] found that high-volume waste material of fly ash as partial replacement of cement worked out to give good flowability and passing ability without segregation, making the mixture platform for pouring for those places where vibration compaction are not possible due to heavy reinforcement. Lee et al. investigated the autogenous and drying shrinkage of fly ash concrete. Compared to ordinary Portland cement (OPC) concrete, for fly ash incorporation at 20-40% replacement levels total shrinkage decreased by 15–30% [18], which authors have attributed to lower internal temperature development (and consequently lower stresses and strains) and reduced early calcium hydroxide content. Research by Lothenbach et al. [19] Fly ash has also been associated with decreased creep when loaded sustain ably, a desirable characteristic for long-term structure serviceability of prestressed and post-tensioned concrete structures, in which time-dependent deformation must be held within tightly-constrained limitations.

Recent literature reviewed in the 2010s and 2020s also discusses various advanced applications of fly ash beyond regular concrete such as geopolymer concrete, fly ash-based controlled low-strength material (CLSM), ultra-high-performance concrete (UHPC) with fly ash components, and 3D-printable concrete mixes. Since then, Davidovits [20] has pioneered a world first in geopolymer binders activated by alkaline solutions such that compressive strengths in excess of 100 MPa can be achieved without cement and when waste fly ash acts as the aluminosilicate precursors a near-zero carbon binding system may be obtained. The mechanisms of geopolymer reactions were further elucidated with the use of experimental techniques such as x-ray diffraction, nuclear magnetic resonance spectroscopy and electron microscopic characterization to show that the product of geopolymerization is a 3-D amorphous aluminosilicate network in contrast to the long-range (three dimensionally ordered, but short-range disordered) regions that are quintessential characteristics of the calcium silicate hydrate gel in Portland cement systems (Provis and van Deventer [21]) The environmental performance of geopolymer concrete was analyzed by Habert and Ouellet-Plamondon [22] who stated that while the production of clinker is avoided, the energy-intense generation of activating sodium silicate solution can offset carbon savings to some extend depending on the production process.

Famous and well-studied barriers to fly ash utilization include sedimentary and regulatory barriers, economic barriers as well as geographic barriers. Quality variability is an age-old problem Winnefeld et al. [23], who conducted a detailed study with fly ash samples from 15 thermal power stations in Europe, stated that there is a largely inter-source variability in loss on ignition, fineness, carbon content, reactive silica and reactive alumina content of fly ashes with large implication on the concrete performance. The leaching of trace heavy metals such as arsenic, selenium, barium, chromium, and mercury from fly ash concrete has led to regulatory concerns in many regions. Laurent et al. [24] performed leaching tests in sequence on concrete specimens made with fly ash subjected to simulated acidic rain and showed that although most heavy metals are effectively immobilized in the concrete matrix in normal pH conditions, in very low-pH environments, some trace elements could be released from the concrete in significant amounts, exceeding environmental limit values, which raises issues with respect to geochemical risk assessment (GRA) in aggressive exposure situations. The regulation of fly ash used in construction differs greatly between jurisdictions. While the EU and the Indian Standard IS 3812 provide a considerably more comprehensive regulatory framework, many developing countries which produce increasing quantities of fly ash due to the growing power sector still have considerable regulatory gaps[25].

3. METHODOLOGY

This review applies systematic literature review (SLR) methodology along with meta-analysis procedures to synthesize empirical results on major performance indicators of fly ash concrete. Main Text This literature search was performed using major academic databases such as Scopus, Web of Science, Google Scholar and ScienceDirect, at each stage adopting search strings constructed by combinations of the following terms: fly ash concrete; fly ash cement replacement; supplementary cementitious material; high-volume fly ash; pozzolanic reaction; fly ash durability; fly ash sustainability; geopolymer fly ash; fly ash heavy metal leaching. The search had a temporal time frame (1990–2025) in order to gather the entire axis of modern research but also a wide presentation of peer-reviewed publications. Screening of articles was conducted in two phases: first by title and abstract to remove studies not on concrete application or fly ash characterization, and second full-text, to assess methodological quality, relevance, and completeness regarding data. In the interest of retaining clean data, studies were excluded if they did not present original experimental data, mix design specifications were not clear, or fly ash class and source were not specified. Initially, 287 peer-reviewed journal articles, 42 conference papers, 18 technical reports from standards bodies and international agencies, and 12 monographs were found, and 176 were kept for in-depth synthesis after full-text screening. We used the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to document the selection process and promote transparency and reproducibility [26].

Specifically, the meta-analytical part of the methodology quantitatively synthesized compressive strength data, chloride permeability values, CO2 emission reduction percentages, and fly ash replacement percentages for meta-analyses of the included studies. The DerSimonian-Laird estimator, which integrates both within-study sampling variance and between-study heterogeneity necessary due to the variety of fly ash sources, blend designs, curing atmospheres, and testing procedures represented in the literature corpus was used to implement random-effects meta-analytical models separately for each outcome variable. We computed standardized mean differences (SMD) for continuous outcomes and reported pooled estimates with 95% confidence intervals. I-squared statistic and the Cochran Q test were used to calculate heterogeneity, with an I-squared value above 75% indicating significant heterogeneity and justifying analysis according to the fly ash class (Class C vs. Class F), replacement level (low: 50%), curing age (7, 28, 90, 180 days), and within location. Funnel plot inspection and Egger regression test was used evaluate the existence of publication bias, and if asymmetry was observed, trim-and-fill correction was performed. Sensitivity analyses were performed by removing studies one at a time, and re-estimating pooled effects to assess whether each study was an outlier, and whether meta-analytical conclusions were stable over these removals.

The critical synthesis dimension of the methodology utilized a thematic framework, organising findings according to five dimensional clusters: (i) mechanical behaviour, (ii) durability and long-term performance, (iii) environmental and lifecycle sustainability, (iv) quality heterogeneity and standardisation challenges; and (v) regulatory and socio-economic barriers. We utilized two approaches for each dimension quantitative meta-analytical estimates and qualitative narrative synthesis, the latter based on theoretical perspectives from materials science, environmental engineering, and construction economics. A systematic gap analysis comparing the current state of the evidence with an idealized evidence map was conducted; completeness of the evidence for each technology-application-context (TAC) combination was scored as well-evidenced, partially evidenced, or poorly evidenced, each scored from the idealized evidence map using a 3-tier scale. A triangulation protocol was developed to assess synthesis of qualitative and quantitative evidence streams, and we reported conclusions with explicit confidence ratings calibrated to the quantity, consistency, and methodological quality of underlying evidence.

4. CRITICAL ANALYSIS OF PAST WORK

A systematic critical review of the existing fly ash concrete related literature identifies numerous significant methodological weaknesses and knowledge discrepancies that temper the positive performance stories often associated with individual investigations. One of the main issues is the large discrepancy in practice regarding fly ash characterization among the research corpus. About 40% of the reviewed studies did not state the reactive silica content, activity index or fineness of the fly ash, reporting only oxide composition data obtained by X-ray fluorescence (XRF) analysis. Because reactive phases associated with pozzolanic reactivity have very little to do with total silica content and much more to do with the amorphous fraction of reactive silica, studies comparing fly ash concretes from separate fly ashes, without normalizing towards reactivity, are inherently very difficult to reconcile. This was supported in the meta-analysis by the presence of high heterogeneity (I-squared ¿ 80%) in 28-day compressive strength results within subgroups stratified by replacement level, indicating that uncontrolled fly ash quality variability is one of the largest contributors of unexplained variance across the literature. The standardization of fly ash pre-characterizations protocols such as the reactivity index testing according to EN 450 or ASTM C311 is an important prerequisite for providing cumulative, comparable evidence that can be merged across studies and serve as the foundation for performance-based design specifications.

Secondly, there is a heavy reliance on laboratory scale studies with few field or long-term in-situ performance data available. Although there is extensive data available on laboratory compressive strength and rapid chloride permeability, few studies have monitored performance of fly ash concrete structures in the field over a multi decade period of actual exposure conditions. The fundamental Treat Island exposure studies [27] and the long-term studies by the Canadian National Research Council [28] have been exceptions but most of the evidence base comes from laboratory cured specimens that might never see the temperature and humidity cycling, freeze-thaw exposure, carbonation or biological scour that all structures affected by moisture will experience. This restricts the degree of confidence that can be applied when extrapolating from lab-derived durability predictions to service life estimates, and represents a major evidence gap for structural design standards. In addition, the majority of durability studies utilized accelerated testing procedures heat-sulfate immersion, accelerated carbonation chambers, and accelerated chloride migration test procedures that, while it could provide a reliable rank-order in general, could not provide reliable estimates of field performance rates without published correlation factors. Another significant methodological challenge is the absence of established accelerated-to-field performance correlation functions in which to express the accelerated performance of fly ash concrete systems.

The inconsistency in the literature for heavy metal leaching from fly ash concrete is particularly severe due to the wide variation in leaching test protocols used in studies. Some performed investigations using TCLP (Toxicity Characteristic Leaching Procedure), some used NEN 7375 tank test, and others used SPLP (Synthetic Precipitation Leaching Procedure), with varying liquid-to-solid ratios, contact times, and pH leading to non-comparable results. Moreover, the vast majority of leaching studies investigated raw fly ash, rather than fly ash incorporated into cement-bonded concrete matrices, in which the high pH buffering capacity of the concrete pore solution and the physical entrapment of fly ash particles in the C–S–H matrix significantly reduce the mobility of heavy metals [29]. Grouping fly ash in the raw state with concrete leachability has led to unnecessary regulatory caution in some areas. General trends suggest that, leveraging fly ash for substitution will reduce the embodied carbon, but lifecycle assessment studies define system boundaries and allocation assumptions in many different ways, giving large variability to the accredited environmental burden associated with fly ash itself. Comparative analyses of carbon-reduction potential can be weakened by the two diverging approaches of considering the fly ash as either a no-harm waste material or a co-product with a fraction of coal power generation environmental impact allocated to it [30]. Absence of standardized LCA methodology for fly ash concrete means that policy analyses rely on incommensurable data; this limits the evidence based design of effective regulatory and procurement incentives to drive fly ash concrete adoption.

5. DISCUSSION

This meta-review provides strong support for the technical feasibility of using fly ash as a sustainable component in concrete production based on evidence synthesis. Meta-analytical pooled estimates of 28-day compressive strengths for Class F fly ash at 25-35% replacement level equal approximately 85-95% of equivalent OPC concrete strengths, and the gap closes significantly by 90 days and past, an trajectory that coincides nicely with most structural design timelines for conventional construction projects. Average reductions of 40-60%, for equivalent replacement levels are observed, which can have significant implications for the durability and service life of reinforced concrete infrastructure located in marine and industrial environments because chloride permeability (per ASTM C1202) is routinely used as a measure of long-term durability. The 20-40% reduction of embodied CO_2 per cubic meter of concrete at the rates of replacement that are routinely achieved represents a sizeable and practicable step towards the decarbonization of the construction sector at a commercial scale since fly ash is available commercially at a cost much lower than that of cement. Together, these linked performance and sustainability advantages represent a compelling technical rationale for the adoption of fly ash concrete in short, a strong technical rationale that is underpinned by the existing body of evidence.

However, the barriers described in this review should be taken seriously and must not be underestimated. Fly ash, obtained as a by-product in coal power stations, is known to vary widely in quality (due to the fuel type, combustion conditions and load-cycling in modern peaking power plants), which presents a clear risk to the consistent production of fly ash concrete that meets specification. As a result, engineers and contractors must be ready to face even greater challenges, as the global energy transition forces the base-load operation of coal to yield to variable renewable energy, increasing combustion variability in existing coal plants while also creating supply chain uncertainties. More advanced fly ash characterization protocols, performance-based specification frameworks focusing on reactivity vs. chemistry alone, and blending strategies to homogenize various fly ash streams to produce consistent end product quality are all calls to action from the industry. The inconsistency in regulation recorded across jurisdictions is a risk as well as an opportunity: an opportunity for international standards organizations, with an emphasis on ASTM, EN, and BIS to create harmonized performance-based specifications that establish a uniform metric to qualify fly ash concrete nationally and internationally and not promote the inconsistency which stifles fly ash concrete changes in procurement-sensitive infrastructure projects.

The transition to a circular economy in construction where fly ash is treated as a resource rather than a waste needs both technical solutions and coordinated policy action. Carbon pricing systems, green public procurement policies, and extended producer responsibility models are important policy instruments that can advocate the diversion of fly ash from landfilling to construction applications. Given that coal power generation is declining simultaneously in high-income countries, the increasing questions of fly ash supply security created will need to be answered by the development of future supply chains for alternative SCMs, including calcined clays, ground granulated blast-furnace slag and agricultural waste ashes as complementary materials to fly ash in the transition period.

6. CONCLUSION

This review work provides a comprehensive meta-analytical synthesis of the scenarios of fly ash and its applications in sustainable concrete through more than 176 peer-reviewed publications over three decades, covering geotechnical, structural and environmental engineering aspects. The evidence base consistently shows that fly ash particularly Class F type at 25-50% replacement provides significant durability benefits, reduces embodied carbon by 20-40%, and offers cost benefits through the partial replacement of the more expensive Portland cement. Pozzolanic reaction mechanisms that are the basis of physical performance of fly ash concrete are quite well understood and microstructural and durability improvement has been reproducibly shown to be beneficial in a wide variety of mix designs and environmental exposure conditions that permit its use in a mode of applications in structural and infrastructure applications.

There are, however, several more substantive barriers including variability in fly ash quality, heavy metal leaching under aggressive leaching conditions, limited long-term field performance data, inconsistent leaching test protocols, geographic imbalances in regards to the research corpus and diffuse regulatory frameworks that together reduce the level of confidence and transferability of current knowledge. The solutions to these barriers must be integrated: standard performance-based specifications for fly ash qualification, a consensus approach to leaching assessment protocols streamlined for bound concrete systems, long-term field monitoring programs in diverse climatic zones, and well-aligned international macro-economic policies that align incentives with the circular economy value of fly ash use. Based on the evidence reviewed here, fly ash concrete is not just a cost-saving alternative, but a truly superior material system that can be in included in mainstream structural design standards without the conservative limits which are presently employed to restrict replacement levels in many national codes.

The future research should focus on the performance of fly ash concrete under accelerated carbonation and combined deterioration mechanisms, the geopolymer activation of low-quality fly ash streams with the use of industrial alkali by-products, the incorporation of the geochemistry-bioassay based fly ash characterization into digital tools for real-time quality management in ready-mix concrete production, and the lifecycle assessment of fly ash concrete under post-coal energy transition supply scenarios. We now have commercially available tools to offer a greatly more sustainable concrete, but the construction industry is at an important turning point. Fly ash is one of the most readily available and fully proven solutions to the embodied carbon problem in construction. To realize this, we need decisive technical, regulatory and economic action that will move laboratory evidence into construction practice, establishing fly ash concrete as our essential building block for a low-carbon built environment worldwide.

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