The call for Global Action Plan

Thermal Plasma for Cement: Horizons in Research & Applications

Advent of Engineered Granulated Cementitious Slag

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I. Background

Cement production is one of the activities pervaded world over with the highest carbon footprint at about 8% of global emission, basically for using coal as the fuel and limestone as the raw material. Of late, though some developments took place to replace coal with biomass, tyres and other waste materials, coal continues to command the dominant portion of fuel input to cement.

Research is in progress to replace coal/fuel with plasma as the thermal source to achieve over 1450 ^{o}C for clinkerisation. As a matter of fact, it is forbidden to think over plasma for cement production availing grid power of coal based thermal power plants (TPPs). One ton of clinker consumes over 0.25 tons of coal in conventional rotary kiln, as against 0.72 tons of coal-equivalent in plasma route, if grid power from TPPs is used.

Whereas, in the case of using nuclear power for plasma, just 36 grams of radio-active material serves the power need of 1.2 MW/ton of clinker, that too in the most benign way on pollution and ecological front.

By the release of nuclear power to private sector through Small Modular Reactors (SMRs), the scenario is totally changed facilitating to deploy plasma technology for process plants. From a socio-economic perspective, SMRs provide distinct advantages that align with concurrent Environmental, Social, and Governance (ESG) criteria.

II. Plasma Technology

Plasma is often called the ‘fourth state of matter’ after solids, liquids, and gases. Plasma technology utilizes a highly energized, super-heated gas known as plasma, generating extreme heat to process materials at industrial scale.

The main difference is that a coal-fire is a chemical reaction of releasing energy through oxidation of carbon whereas plasma flame is the sustained state of electrically charged particles.

While generating Coal-fired flame, large volumes of carbon dioxide (CO_2), nitrogen oxides (NOx) sulphur dioxide (SO_2), and massive amounts of solid residual bottom ash and fly ash are produced; whereas, flame out of plasma torches generates zero inherent combustion emissions because it does not involve to burn any fuel.

While coal fire generally reaches temperatures between 800°C to 1,500°C, depending on the airflow, boiler setup, and coal quality, Plasma Flame reaches extreme temperatures starting from 3,000°C to well over 10,000°C, making it significantly hotter than any chemical/fuel fire.

This extreme heat generated by thermal plasma torches can melt, vaporize, or chemically reconfigure any known material as well, turn metals, byproducts and rocks into molten state. Such engineered molten matter, upon rapid quenching, form into glassy slag and, in turn, ground to cement for Ultra-high-Strength Geopolymer Concrete.

III. Logistical opportunity for transition to Plasma

Since the basic input for plasma is electricity, it is prohibitive to think of plasma as heat source for processing plants or cement production. However, owing to the improvements in generation of nuclear power (NP) with due safeguards, which is sustainable, cost effective and emission-free, tapping nuclear power for plasma technology has drawn attention of the researchers and industries.

Pressure on industries for clean and green technologies is the global imperative that can be addressed by NP-Plasma for following specific reasons.

- Performance wise, the power generation out of 20,000 kg of coal can be met by 1 kg of radio-active material.

- The life of a nuclear power plant is more than 60 years as against 20 years of coal based thermal power plant (TPP).

- But for initial capital cost, the maintenance and spares cost of nuclear power plant is fractional against that of coal-based TPPs.

- Operationally nuclear power plant is clean and green as against TPPs with complex flue gases and solid wastes such as fly ash posing environmental challenge.

- By the advent of small modular reactors (SMRs) enabling the participation of private sector in captive nuclear power production world over, gates are opened up for plasma technology in providing cost-effective, sustained and clean thermal energy. While Russia and China are way ahead with operating plants, USA, Canada, India, Brazil, South Korea, UK and France are at various stages of implementation.

- Notwithstanding captive SMRs, industries may also form into syndicates to patronise large nuclear power plants, in order to draw electricity through grid network.

IV. Plasmology-Research for cement production at global level

Besides hydraulic cement production, the Researchers at INSWAREB have envisaged to produce Engineered Granulated Cementitious Slag (EGCS) through plasma route, availing the legacy ash accumulated in ash ponds of TPPs. Since both power and fly ash are the raw materials at the command of TPPs, this technology proves as synergy to hundreds of TPPs all over the world, as a solution to their issues on pollution, waste utilisation and carbon footprint.

Upon reviewing the plasma research for manufacturing cement at global perspective, four initiatives are evident in Europe and USA as narrated below:

1. As part of the EU-funded ELECTRA project consortium, Heidelberg Materials achieved a major breakthrough in producing clinker at its Slite Cement plant on the island of Gotland, Sweden. They developed and tested a 300 kW_e pilot-scale rotary kiln utilizing a CO_2-based thermal plasma system as the high-temperature heat source, replacing fossil fuel totally. Carbon dioxide gas is heated to over 5,000°C to create a plasma jet that melts the raw mix towards clinkerisation. As announced in Feb-2025, the pilot reported to have achieved 54 hours of continuous operation resulting to have a clinker that contains smaller, highly uniform alite crystals, indicating the production of a more reactive cement with no contamination from fuel ash. Following these results that encourages to shift the technology away from simple batch testing to a viable continuous manufacturing process, plans are underway to scale up to a 1 MW_e plasma kiln with a projected output of over 20 TPD.

2. In mid-2025, Holcim, the building solutions giant, reportedly partnered with SaltX Technology, a Swedish firm focusing on electrifying heavy industries to scale up an all-electric, electric plasma kiln concept capable of reaching the necessary 1,450°C for clinker manufacturing using entirely renewable grid electricity. The Electric Arc Calcination technology concentrates primary material carbon emissions directly at the source, paving the way for commercial "near-zero" carbon cement at scale.

3. In late 2025, high-tech plasma developer, PyroGenesis reported to have signed a contract with a major European cement producer to deliver an industrial plasma torch system which is integrated into an industrial calcination kiln. It specifically targets the calcination stage needed to decarbonize limestone by replacing the fossil-fuel burners with plasma torches.

4. As part of the academic and technological research, researchers at the University of Florida have reportedly developed a ‘high-temperature plasma arc reactor (HiPAR)’ specifically engineered for Portland cement clinker synthesis. The HiPAR at its 25 kW power rate, aims to replace the rotary kilns by creating a hyper-controlled thermal environment. It is aimed to produce uncontaminated clinker while cleanly processing

alternative raw materials and industrial byproducts (like slag and chemically treated fly ash) into high-performance cementitious matrices.

Though the latest tie up between IIT-NCCBM in India is a welcome step, in the absence of pilot plants for advanced studies, their preliminary research on plasmology does not add value on cement front against the strides already scaled by Heidelberg, Florida University and others as of now.

Focal issues in above studies:

While pilot studies have proven that plasma can successfully synthesize high-quality alite and belite phases, engineering teams are focusing on optimizing two main physical phenomena:

- Conventional coal flames are highly emissive due to glowing soot particles, which transfer heat effectively via radiation. The plasma gas lacks these particles, meaning pilots are redefining internal kiln geometries and wall refractories to maximize convective and radiative heat transfer to the material bed.
- Researchers are validating the loop of recycling the captured process CO_2 as the plasma ionization gas itself. This eliminates the need for expensive noble gases (like argon) and creates a circular chemical loop inside the plant, as well brings down carbon footprint.

V. Engineered Granulated Cementitious Slag

Notwithstanding production of hydraulic OPC with plasma, INSWAREB has conceptualised to produce a unique cementitious product christened as 'Engineered Granulated Cementitious Slag (EGCS)' based on specific material science-principles and opportunities:

Principle 1: Ultra-high temperature of plasma is conducive to produce amorphous granulated slag with pronounced raw meal design, which would be superior to other granulated slags or crystallined hydraulic cement such as OPC in terms of concrete performance.

Principle 2: Geopolymer concrete consisting of engineered slags such as EGCS, render ultra-high strengths, dense microstructure and centuries of service life as against that of hydraulic cements and other geopolymer concretes (GPCs) in practice.

Opportunity 1: Byproducts such as fly ash and slag need specific qualifications to be blended with hydraulic cement. Whereas, such byproducts can be accepted in their native state to manufacture high-value EGCS since their nativity is transformed by getting molten in plasma. Thus, maximum chunk of byproducts can be roped in duly balanced of their raw mix design with due corrective inputs. This opens up gates for 2.86 billion tons of pond ash occupying over 26,000 ha of land in India.

Opportunity 2: Hydraulic OPC needs lime of specific purity (over 60%) whereas EGCS can accept lime of around 25% purity. This would rope in abandoned or untapped limestone quarries of low purity.

Background of polymer concrete

Though polymer concrete is discussed over the last three decades, it could not make sizeable inroads into the applicational domain of hydrated cement-concrete due to certain techno-economic constraints.

Organic polymer concrete (Opc) failed to replace traditional hydrated cement-concrete because of prohibitive material costs, vulnerability to heat, and a total mismatch with global high-volume construction logistics. While it boasts incredible compressive strengths and lightning-fast curing regimes, it remains a specialty niche material rather than a viable alternative for structural engineering applications. There are several fundamental engineering, economic, and logistical barriers that blocked its widespread market adoption.

To overcome the deficiencies of Opc, Inorganic Polymer Concrete (IPC) otherwise called as geopolymer concrete (GPC) is developed bypassing carbon-chain entirely. It uses the alkaline chemical solutions to activate industrial aluminosilicate powders (like fly ash or Ground Granulated Blast furnace Slag), that triggers polycondensation, forming a geopolymer chain of ferro-aluminosilicate network, –Si–O–Al–O–Fe–O–Si–O–.

Unique features of ground EGCS:

While ground EGCS (GEGCS) is technically an advanced binder, duly added with a powderous activator towards inorganic polymer chemistry, it fundamentally differs from standard Inorganic Polymer Concrete (IPC) in preparation and applicational comfort. The GEGCS, basically composed of lime (20-25%), Silica, alumina and ferrous oxides (80-75%) in prescribed moduli, is quenched through a well defined 'rapid temperature drop down regime (RTDDR)' facilitating almost total glassy formation that responds instantaneously to alkali activation. Thus, the GEGCS blended with its activator can be bagged and marketed in the commercial lines of the cement.

Core Comparison: Conventional GPC vs. GEGCS-GPC

The critical difference lies in how the raw materials are prepared. Conventional GPC uses raw, untreated byproducts that are chemically inconsistent, whereas GEGCS-GPC is the derivative of EGCS, a technically specified raw meal design duly engineered for plasma-pyrochemical melting process to optimize the glass phase at the molecular level.

Feature / Property	**Conventional GPC**	**GEGCS-GPC**
Raw Material State	Raw, variable byproducts (Untreated Class F/C Fly Ash, raw GBFS, or metakaolin).	Plasma-synthesized mineral glass (an engineered, homogenized mix melted at over 1600°C via plasma kilns/reactors).

Mineral Phase Uniformity for Reactivity	Low to Moderate. Raw fly ash and slags contain unreactive crystalline phases, unburnt carbon, and variable particle shapes that hinder full polymerisation.	Near 100% Amorphous Reactive Phase. Plasma processing destroys all crystalline materials, ensuring every single particle participates in glass formation and, in turn, polymerisation.
Chemistry Requirements of Activators	Aggressive & Corrosive. Requires concentrated, expensive, Sodium Hydroxide (NaOH) or Sodium Silicate (Na_2SiO_3) solutions.	Mild & Cost-Effective. Because the EGCS glass is highly reactive, it can be activated with cost-effective safer powders like Sodium Carbonate (Na_2CO_3) or Sodium Sulfate (Na_2SO_4).
Rheology & Workability (Clumping)	Prone to flash-setting, high drying shrinkage, and severe clumping when mixing high steel-fiber volumes.	Highly stable, predictable 1.5 to 3-hour workability window with engineered rheology sequencing to easily suspend heavy fiber loads.
Compressive Strength	Typically, 40 MPa to 80 MPa under ambient curing.	Ultra-High Performance reaching up to 200 MPa.

Projected features of GEGCS in outperforming hydrated cements including conventional GPC

EGCS framework, conceived by INSWAREB, is feasible only through plasma technology to melt and perfectly fuse an 'engineered raw meal design'. Resultant product would be a uniform high-density glass that, upon grinding, responds to polymerization even with mild alkalis into an exceptionally stronger matrix resulting in ultra-high-performance concrete (UHPC).

Because the plasma heat imparts high structural potential energy into the EGCS mineral glass, the GEGCS gets activated readily using benign, dry salt powders blended directly into the mix, requiring only water on-site. Such feature not only enables the product to be sold commercially in bags like hydraulic OPC, but also makes it compatible with RMC activity.

The GEGCS overcomes the limitations of conventional concrete by undergoing geopolymerization to create a cross-linked mineral structure that achieves ultra-high engineering performance (200 MPa).

Conventional GPC relies on the 'chance opportunities' with regard to the chemical composition of raw byproducts. For example, raw fly ash may vary in its reactive alumina-to-silica ratio depending on the day's coal burn.

Conventional GPC is liable to suffer from drying shrinkage and micro-cracking over time due to unreactive particle cores absorbing moisture unevenly. The ultra-dense, completely reacted gel structure of GEGCS concrete does maximize packing density at the nano-scale, effectively squeezing out capillary voids and yielding near-zero permeability.

Applicational scope of GEGCS

Breaking the barriers for cementitious slag in competing with age-old OPC on techno-applicational logistics, GEGCS is likely to emerge as the new wave cement to be sold at par with OPC in bagged condition for the day-to-day applications, with amenability to mix in conventional concrete mixers up to planetary mixers of RMC plants.

Being the media for ultra-high strength concrete, overcoming the constraints with conventional GPC, GEGCS is going to bring a breakthrough in the construction world.

Facilitating to produce ultra-high-performance concrete (UHPC), GEGCS is likely to usher in structural revolution with design of slender structural elements. Such design-rationalisation leads to economise the ultimate costs of structure, with predominant benefit to infrastructure projects.

The convention of 'more cement for high strength' is going to be rewritten as 'less cement but high strength' practice. Problems associated with alite-OPC concrete such as surplus lime, vulnerable transition zone, lime-associated deleterious reactions at late age, high heat of hydration, thermal cracks are grossly addressed. All in all, GEGCS-concrete is the green material by virtue of resource conservation, prolonged service life and reducing carbon footprint.

VI. Action plan to tap plasmology for cement and EGCS production

In view of the ecological and environmental mileage, it is necessary to pursue this subject as global program with the following operational action plan:

1) It is desirable to review the progress of Heidelberg and pursue the research thereon with specific focus on scaling up from their pilot plant capacities. If accessible, it is better to initiate the pilot studies on EGCS in collaboration with Heidelberg with specific focus on:

- Heat dispersion in the kiln
- Production of Plasma torches with long flame-length
- Kiln geometry and wall refractory conducive to plasma burners

2) Alternate to above, the HiPAR of Florida University may be availed that may give half a ton of EGCS per day based on its power rate of 25 kW_e.

3) To kick start the commercial plant, low-capacity plants be focused initially compensating the cost over runs to these 1st batch plants through International Monetary Funds.

4) A few tons of EGCS may be produced at lab/pilot level to evaluate its compatibility for geopolymer concrete. All structural engineering studies be established before embarking upon commercial plants.

5) Since TPPs would be benefitted to resolve their burden of fly ash utilization, pilot plants of 100-500 TPD adjoining to power plants to be funded, providing the power from their captive generation initially. EGCS can be produced availing the fly ash and power from the captive sources. Upon accomplishing the operations, the power can be replaced by that of captive SMRs or syndicated nuclear power plants.

Conclusion

It is not undermining to point out that the contributions of the circular economy and sustainable practices constitute only a small fraction of the global rate of natural resource depletion. According to the data-driven Global Circularity Gap Report co-authored by Deloitte, the global circularity rate sits at just 6.9%, ringing alarm bells on the inevitable truth that over 93% of all materials pouring into the global economy are virgin resources stripped directly from the Mother Earth. This trend proves that our actions inherit the globe to only a few future generations, making a mockery of the Sustainable Development agenda. This agenda should become a spiritual commitment for governments rather than a populist or opportunist tool.

Unabated population growth, rapid urbanization and massive infrastructure development are continuing to cast serious strain on ecology. Tapping the potential of alternate materials and eco-friendly technologies are the need of the hour and summons for global action. UN bodies and International monetary Institutions should focus on technological solutions such as irradiated complementary cement materials (ICCMs), thermal plasma for producing cement and cementitious materials, by supporting the development of plant engineering and applicational research. Plasma technology with nuclear power should go hand in hand to impart true contribution on ecological front. Such combination becomes the high-profile-practice, needing the back up of corresponding governments.

Having catalyzed the fly ash brick production all over India by not invoking their patent, owing to its service to Ecology-Environment-Economy-Empowerment (E^4), INSWAREB believes that tapping thermal plasma for cement and other process industries is another such fete at macro level and, the Researchers are confident that the call given by this paper catalyzes the action plan at higher echelon of all countries having wherewithal to tap nuclear power.
