



Advancing Low-Carbon Concrete: Early Strength Development through Hydration Efficiency Modifier-Based Admixture Technology

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Abstract : The prime agenda of this article is to raise awareness about the present condition of the national construction industry; we have to strive to achieve the Vikshit Bharat 2047 objective that is inspired by our Honourable Prime Minister, **Mr. Narendra Modi**. Vikshit Bharat in this case means the ambitious plans of India to make India a complete, self-sufficient and a wealthy country by the year 2047, which is the 100th year of Indian independence. It is concerned with economic development, social development, good governance, as well as environmental sustainability. **Geopolitically, India is one of the nations that are keen on the 17 SDGs of the United Nations. The research will make nation to make contributions in the attainment of SDGs 12 and 13.**

IndexTerms - Vikshit Bharat 2047, National Construction Industry, 17 SDGs, United Nations, Sustainability

I. INTRODUCTION

When we are talking of sustainability in the realm of the concrete business, concrete being the second highest consumable in the world we must be creative with a commodity twist in mind, a solution that can be easily availed, commercialize business a bit and save a lot of carbon footprint. BIS has also enabled this impetus with reference to the recent amendments of the IS 456:2000, Amendment no 6 (June 2024) which states that Fly ash may be used as mineral admixture 35% when used in single SCM, and as mineral admixture 20% when used in triple blend ,SCM may increase up to 50 % under this condition with this amendment no 11.3 of the IS 456:2000 is now getting complied . The majority of the cases that add the entire potential of SCM that are permitted in the IS code, provides delay in the strength development.

Currently in India the per day execution rate is approximately (27 to 34) Km in case of National highway, 0.2km in case of metro rail, 0.3km in case of structural progress of bullet train and 0.6 to 1MW capacity of hyperscale data centre, 1111 Sqf/day in residential sector. Project management point of view, more than a larger part of the industry early strength development is directly related to progress.

II. STRATEGIC FRAMEWORK

Supplementary cementitious material does not actively participate in preliminary hydration process of the concrete, consequently in the double and triple mixture blend of cementitious mix concrete requires time to build a strength. Provided that we could optimize the secondary hydration process in concrete sooner, the bottleneck of the initial development of the strength will be eliminated. Now, we should learn what is the situation in detail.

III. HYDRATION OF CONCRETE

The hydration of cementitious binders imparted with additional cementitious materials like Fly ash and Ground granulated blast furnace slag occurs in successive steps of physicochemical reactions. These phases are defined by growing cumulative hydration and gradual formation of the major hydration items, that is to say Calcium silicate hydrate, Calcium hydroxide, and Ettringite. The successive transition between one phase to another is controlled by the interactions between nucleation kinetics, ionic supersaturation, pore filling and diffusion constraints in the hydrating microstructure. To know the trigger points of hydrations in concrete, we have done number of trials to know about this

3.1 Initial film stage

The first stage of the process is the film stage where cumulative hydration is minimal and is usually between 0.5 and 3 percent. Already at this initial phase, certain quantifiable amounts of hydration products start to take shape. C-S-H is formed between the approximate range of 1.14-6.83 kg with 0.35-2.10 kg of calcium hydroxide and 0.053-0.315 kg of ettringite. Such products are mainly as a result of the quick dissolution of the most reactive phases of clinker upon the addition of water. Since the hydration products crystallize around the cement particles, they inhibit a film of CS-H slowly on the surfaces of particles. This film starts to

form such that additional dissolution is more or less inhibited, thus reaching the conditions that result in the dormancy period run by the nucleation process.

3.2 Dormant stage

After this initial response, the system passes through the dormant stage at which the cumulative hydration gains slightly, to around 3 percent-10 percent. At this stage, the rate of hydration is reduced significantly although the system is still chemically active. The level of C-S-H also reaches about 6.83- 22.75 kg, and at the same time, the level of calcium hydroxide production reaches 2.10-7.00 kg, and the level of ettringite formation is 0.315-1.05 kg. Even though the reaction seems to be slow there are significant chemical processes occurring in the pore solution. The concentration of calcium, hydroxyl and aluminate ions builds up gradually forming an oversaturated state. As soon as the amount of these ions reaches the level of nucleation, the accelerated precipitation of hydration products occurs again, and the transition to the acceleration stage begins.

3.3 Acceleration stage

The acceleration phase is the phase when hydration is the most active. At this point, cumulative hydration is about 10% -25 percent and hydration products are formed at a tremendous rate. The quantity of C-S-H increases drastically by about 22.75 kg to 56.88 kg and calcium hydroxide by 7.00 kg to an approximate of 17.50 kg. The formation of ettringite also increases significantly to the point of 1.05-2.625 kg. The stage is marked by fast nucleation and growth of C-S-H which gradually occupies capillary pores to create an interlocked microstructural structure in the cement paste. With an increase in the microstructure density, internal diffusion pathways start to get narrow, and resistance to ion transport gradually rises. This increases diffusion resistance and ultimately diminishes the rate of the reaction and begins the deceleration phase.

3.4 Deceleration stage

In the deceleration phase, the cumulative hydration is usually at approximately 25-40 percent. It gets more and more gradually hydrated as the movement of water and dissolved ions remains increasingly inhibited by the solid skeleton. During this period, C-S-H is even more increased to about 91.00 kg as against 56.88 kg and calcium hydroxide is increased 17.50 kg to about 28.00 kg. The growth of ettringite falls between 2.625-4.20kg. At this point the gypsum that is within the system starts to be depleted and this changes the reaction pathways of the aluminate phases. Consequently, conversion of AFt to AFm can be possible, which is an indication of the changing sulphate equilibrium in the cementitious matrix.

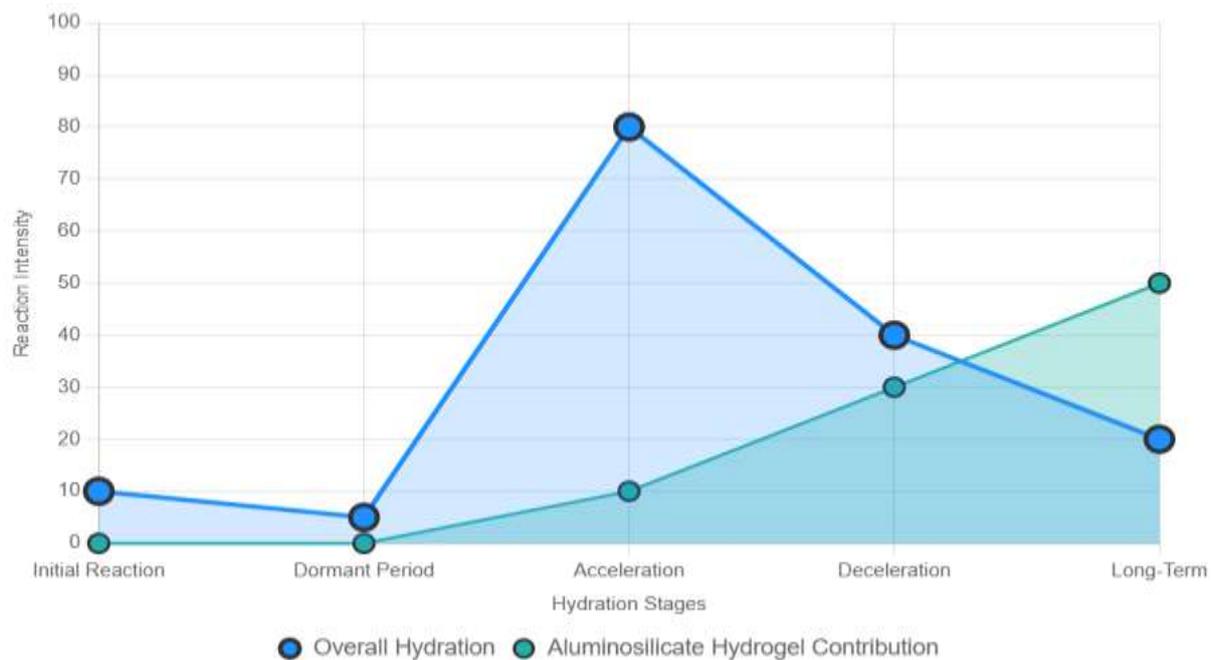
3.5 Secondary reactions stage

As hydration progresses beyond approximately forty percent, the system increasingly becomes influenced by secondary reactions, particularly in binders containing large proportions of supplementary cementitious materials. In this stage, cumulative hydration typically falls within the range of 40%–70%. The quantity of C–S–H rises substantially from 91.00 kg to about 159.25 kg, while calcium hydroxide increases from 28.00 kg to approximately 49.00 kg, and ettringite formation progresses from 4.20 kg to about 7.35 kg. The most important mechanism during this stage is the pozzolanic consumption of calcium hydroxide. Reactive silica and alumina phases present in fly ash and slag react with the accumulated calcium hydroxide to produce additional secondary C–S–H. This reaction significantly improves hydration efficiency by converting an otherwise less structurally beneficial phase into additional strength-contributing gel, thereby densifying the microstructure and enhancing long-term mechanical performance.

3.6 Long-term stage

Finally, the hydration process reaches the long-term stage, where cumulative hydration gradually approaches 70%–100%. By this time, the total amount of C–S–H may increase from 159.25 kg to approximately 227.50 kg, while calcium hydroxide content grows from 49.00 kg to around 70.00 kg. Ettringite formation continues to evolve slowly, increasing from 7.35 kg to roughly 10.50 kg. Hydration kinetics during this stage are predominantly controlled by diffusion limitations, as the dense microstructure formed during earlier stages restricts the movement of water and ions toward un-hydrated cement particles. Consequently, hydration proceeds very slowly but continues over extended periods, resulting in gradual improvements in strength and durability.

Taken together, these stages illustrate how the hydration process evolves quantitatively from the earliest nucleation-controlled reactions to the diffusion-limited long-term regime. In systems incorporating supplementary cementitious materials, the later stages—particularly those involving secondary pozzolanic reactions—play a critical role in improving hydration efficiency and generating additional C–S–H, which ultimately contributes to the enhanced long-term performance and sustainability of the concrete matrix.



IV. TECHNOLOGICAL INTERVENTION

In this process if we can arrange to put some alumina in the deceleration stage then it will accelerate the secondary hydration process. Here we must use appropriate HEM, as it focuses on improving the rate and efficiency of cement hydration during the curing process. The hydration of cement involves a chemical reaction between water and the minerals in cement, primarily tricalcium silicate (C_3S) and dicalcium silicate (C_2S). Enhancing hydration efficiency typically leads to faster strength development, better durability, and more sustainable concrete.

V. INTEGRATION OF THE TECHNOLOGY INTO ADMIXTURE

The technology behind this enhancement typically involves the use of various chemical admixtures or additives that improve the hydration process. Hydration Efficiency Modifier (HEM) was developed. The underlying objective of this approach is to improve the kinetic interaction between clinker hydration products and SCM particles, thereby accelerating the secondary hydration pathway without increasing clinker content.

The technology relies on a synergistic blend of multifunctional alkanolamine-based hydration promoters and catalytic modifiers. These compounds interact with early hydration phases of cement, influencing the dissolution and re-precipitation behaviour of calcium-bearing phases and enhancing the availability of reactive calcium ions. As a result, the activation of latent hydraulic and pozzolanic materials becomes more efficient, particularly in systems containing high volumes of SCMs.

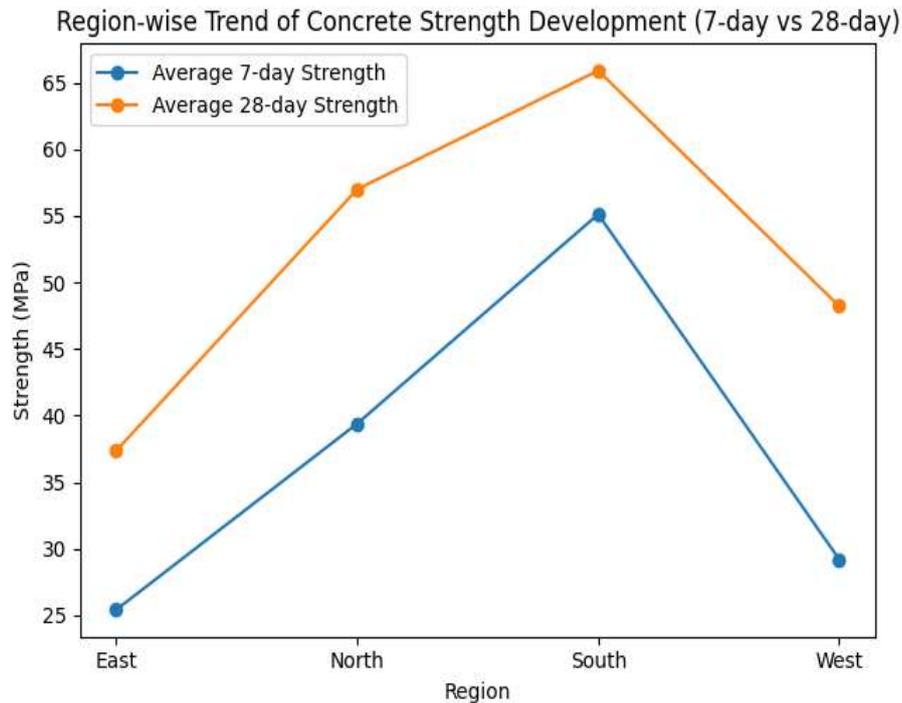
The formulation uses a carefully optimized combination of amine-based hydration promoters, commonly discussed in cement chemistry literature for their influence on hydration kinetics. While several classes of these compounds are known to act as grinding aids and hydration catalysts, their performance in high-SCM concrete systems depends strongly on molecular structure, dosage optimization, and interaction with the mineralogical composition of the binder system.

Through controlled laboratory and field investigations, the hydration efficiency modifier demonstrated the ability to improve early-age strength development in concrete containing significant proportions of fly ash, GGBS and slag, while preserving the sustainability benefits associated with clinker reduction. This approach therefore provides a viable pathway for producing lower-carbon concrete without compromising construction productivity or structural performance.

VI. TESTING AND OBSERVATIONS

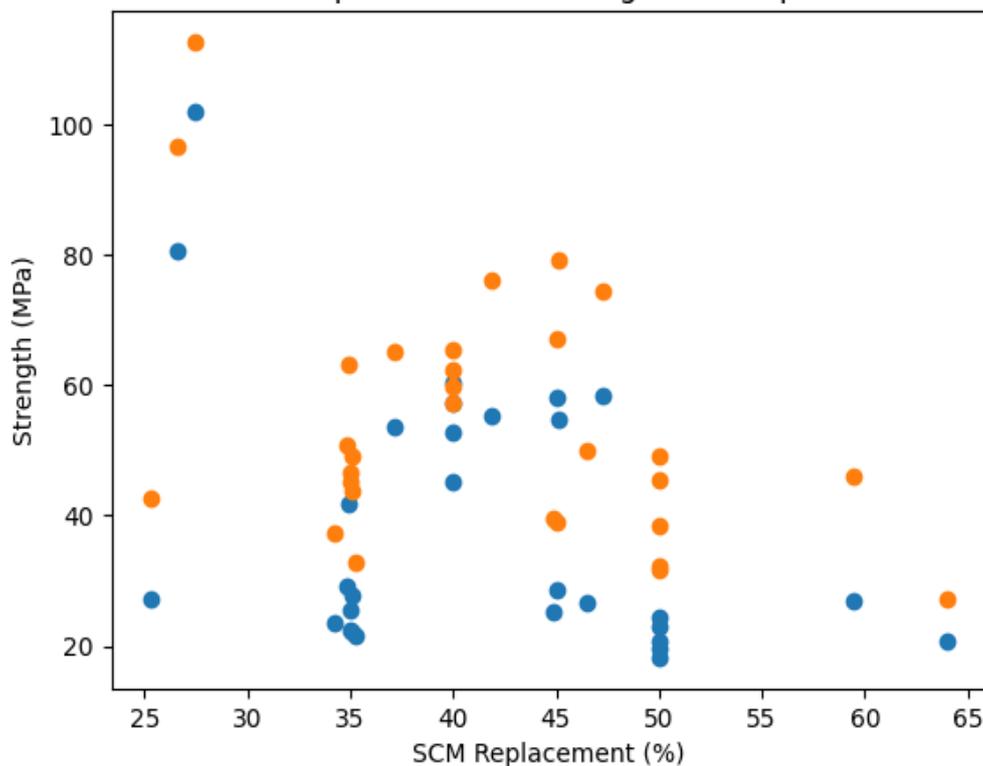
All across the nation at different geography testing and observation has been conducted, it has been found that quality index of cement and cementitious material plays a crucial role in the success of this technology. More importantly a particular quantum of cementitious demands specific nutrition of alkanolamine-based hydration promoters and catalytic modifiers. **With reference to the SCM replacement, respectively 35% of fly ash and 50% of GGBS in concrete in the double blend category gains 70% to 84% strength development of F_{ck} in 7 days, based on inherent quality of raw materials. For triple blend also the results obtained in a almost same rage.**

In the instances of triple blend cementitious in the concrete, a higher percentage of the percentage of SCM type to be preference to the respective application of Hydration Efficiency Modifier. The most valuable and significant observation has been in the conventional reinforced cement concrete (RCC) systems, which are produced by only cement as a binder, the aggregates of grade limiting distribution is controlled by the limits of gradation provided in the IS 383. In this grading system, the finer particles smaller than about 150 μm would be classified in the pan fraction in the sieve analysis resulting in the mineral filler contribution in the cement matrix being highly dependent on the cement itself. Normal cement generally adds particles into the smaller size range especially at 90 μm , 75 μm , and 45 μm . As a result, in a particle packing sense the gradation continuity between the finest aggregate fraction and the cementitious matrix is not particularly large.



But when additional cementitious materials are added with the help of double-blend and triple-blend cementitious binder systems, the range of micro-fillers is greatly extended. Other materials like Fly ash and Ground granulated blast furnace slag have naturally fine and diversified particle size distributions than the ordinary cement. They are effective in closing the size gaps between the intermediate particles in the grading curve which enhances the overall weight density of the binder matrix. This gives the granulometric continuity and leads to improved pore refinement, enhanced workability, and increased kinetics of hydration. Consequently, blended binder systems give a better optimized structure of particles packing inside the concrete matrix that allows the concrete to perform better and be more durable than traditional single-cement systems. Consequently, the lesser the permeability the more durable it becomes.

SCM Replacement vs Strength Development



VII. VALUE ADDED ADVANTAGES OF THE TECHNOLOGY

As the objective of the research has been to allow early strength development tendency in the replaced SCM concrete to the highest allowed limits, we should also consider the other aspects and the possible benefits of this technology. This will be the additional advantage in the rational conclusion part.

- A. Inclusion of pozzolanic efficiency modifying technologies into the modern concrete systems has come up as a good strategy of enhancing sustainability as well as mechanical performance. These technologies help minimize the carbon intensity of the traditional cement-based construction by helping to better utilize supplementary cementitious materials. The Portland cement in the binder system can be partially substituted with materials like Fly ash and Silica fume thus

reducing the number of clinkers needed in the manufacture of concrete. The high level of energy consumed, and the generation of carbon, during the process of clinker manufacturing, which comprises the most intensive process of cement production, makes the augmented utilization of these pozzolanic constituents play a major role in reducing the total carbon footprint of the concrete matrix, but with no effect on the structural performance.

- B. This enhances efficiency in hydration resulting in a denser and finer microstructure allowing more efficient use of cement particles and eliminating the occurrence of unreacted phases. As a result, the concrete has increased compressive strength and better tensile and flexural behaviour that is important parameter in structural resiliency especially in an area characterized by dynamic or seismic load events.
- C. The other benefit of such hydration-optimizing technologies is an enhancement of crack resistance and microstructural integrity. The micro voids formation in the hardened matrix is minimized by encouraging homogenous hydration and improving the distribution of the reaction products. By increasing the density of the internal structure, stress concentration at the pores and partially hydrated cement particles is reduced and therefore enhances the fatigue resistance of the material. The microstructure refinement raises repetitive loading and other environmental stresses of concrete, which, eventually, leads to increased durability and structural reliability of the structure throughout the service life.
- D. The density and functional cementitious systems can be significantly affected by use of pozzolanic efficiency modifying technologies. These technologies enhance a more thorough reaction between cementitious binder's clinker phases and auxiliary reactive constituents by enhancing the hydration kinetics of the cementitious binders. This increases hydration and as a result more calcium-silicate-hydrate (C-S-H) gel is formed that gradually fills up the capillary pores in the cement matrix. This causes an increase in the density and reduced permeability of the resulting microstructure, increasing internal porosity and enhancing the overall integrity of the hardened concrete. A small and highly developed microstructure is linked directly to better stability in the mechanism of micro-mechanical stability and better resistance to environmental degradation mechanisms since there is fewer interconnecting voids in the hardened matrix.
- E. Optimized hydration systems can also be useful in functional performance in specialized structural applications, including radiation-resistant construction, in addition to increased density. Properly designed cementitious matrices with hydration efficiency technologies have the ability to receive additives with hydrogen-bearing or neutron-absorbing elements. Elements like boron or hydrogen-based materials are known to increase the level of attenuation of neutron radiation in shielding structures. This process is also facilitated by the densification of the microstructure that reduces the internal void pathways that may otherwise allow the transmission of radiations. It follows that concrete systems constructed having better hydration efficiency and appropriate functional additives can exhibit better neutron shielding capacity and become potentially valuable in the infrastructure relating to nuclear plants, medical radiation conditions or any other application where radiation attenuation is required.

VIII. LIMITATIONS OF THE TECHNOLOGY

We need to remember that success of this technology is depending upon the optimum utilization of the proportion of amines with respect to cementitious content and the quality index of the cement as well as SCM (From product quality standpoint any SCM & Cement conforming to IS codes is good to go for the usage of this technology), and accordingly dosage can be figured out else following are the consequences.

The use of hydration efficiency modifier technology in concrete admixtures formulations can cause a number of performance-related constraints in some circumstances involving cement and supplementary cementitious material (SCM). The uncontrolled acceleration of tricalcium aluminate hydration is one of the main issues, especially in cases when cement contains a rather high content of C3A (>8-10%). In this case, the existence of these amine compounds can encourage quick hydration responses, leading to quick slump loss, premature hardening of the concrete matrix, and if these cement systems may predispose the danger of flash set in the concrete, which in turn may lead to pumping challenges during the concrete placement activities. Also, the existence of these amines can be related to the diminished workability retention, usually reflected in an accelerated rise in viscosity with time thus restricting the handling and transportation period of fresh concrete.

The other major constraint is observed in sulphate-imbalanced cement systems, especially that which is low in gypsum ratios, high in hemihydrate ratios or extremely high in cement fineness of about 400 m²/kg Blaine. Under these circumstances, the amine-based compounds in terms of interaction with the aluminate-sulphate equilibrium may result in an increased risk of false set or flash set phenomenon, which will negatively impact the workability and control of the concrete mix. Also, in admixture formulations, they are alkaline amines, which could affect storage stability and shelf life of the product, cause gradual pH shift and increase in viscosity during extended storage and can cause a change in the consistency and dosing behaviour of the admixture in the long term.

The problems related to these compounds might be increased when additional cementitious compounds like Fly Ash and Ground Granulated Blast Furnace Slag have erratic quality properties. Even with a constant dosage of admixtures, the parameters of fineness, carbon content, or chemical composition may cause major variation in the properties of fresh and hardened concrete. In this case, the dosage of admixture can give varied rheological behaviour on different days with significant variations in early-age strength development, especially at the age of 1 day and 3 days. This makes it difficult to preserve the early strength specifications as a batch of concrete can be high in early strength and the next batch will be hindered in growth and development of strength and hence control of the process and assurance of quality construction in the engineering field is difficult to manage.

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