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Escalating The Durability Of Concrete Structures Using Engineered Cementitious Composites

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ABSTRACT
Concrete can be damaged by various stimuli, responsible for its deterioration. Intrinsic factors like construction deficiency and design deficiency may have adverse effects on concrete strength and durability. On the other hand extrinsic factors like Chloride attack and Sulfate attack and their effect on concrete structures can be minimized by the use of Engineered Cementitious Composites (ECC). The concrete distress can be minimized by using Polyvinyl Alcohol (PVA) Fiber Reinforced Concrete. This paper imparts the knowledge about the various causes and stages of concrete distress, depicts the tensile behaviour of ECC with tight crack widths and durability properties of ECC such as Rapid Chloride Penetration Test and Permeability Test for 2% PVA fiber by Volume of Concrete.

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I. INTRODUCTION

Durability of concrete may be defined as the ability to resist weathering action, chemical attack, abrasion, or any process of deterioration. Durability is the ability to last a long time without significant deterioration as expressed by the Portland Cement Association. Concrete durability has been defined by the American Concrete Institute as its resistance to weathering action, chemical attack, abrasion and other degradation processes. Durability of concrete can be defined as the ability to perform satisfactorily in the exposure condition to which it is subjected over an intended period of time with minimum maintenance.

Portland cement concrete is widely available throughout the world but the technology and skill required to proportion, mix, place, and cure it for long-term durability has not yet spread as widely as is necessary. This should be the priority for the next century. The knowledge exists to select materials, proportion them appropriately, mix them thoroughly, transport and place them without segregation and cure them to minimize cracking and optimize long-term strength development and durability. Implementing this knowledge is a major challenge. The Concrete Engineer should concentrate on a more permanent, low-maintenance infrastructure. As a consequence, it will be possible to spend valuable material resources on infrastructural developments instead of spending more and more money on replacing or maintaining a deteriorating system. Every concrete mixture should be proportioned in accordance with exposure conditions, construction considerations, and structural criteria. Exposure to freezing and thawing, sulfates, deicing chemicals, acids, varying moisture conditions and abrasive loadings should all be considered when selecting materials and proportions.

.In spite of the advances in producing the high strength concrete, infrastructure all over the world are suffering from deterioration and damage when exposed to real and aggressive environments. Structures seldom fail due to lack of intrinsic strength but due to Serviceability failures. The American Society of Civil Engineers 1998 Report graded the state of American Infrastructure with an average D (Poor). This report also required an investment of some $1.3 trillion to put the roads, bridges, and water/waste/energy utilities to good working order. In 2005, the investment needed was $1.6 trillion to raise the quality of America's infrastructure to a satisfactory level. The New Civil Engineer (NCE)/Institution of Civil Engineers (ICE) State of the Nation Report in winter 2001 graded the overall quality of the UK Infrastructure as C (Average). It is reported that repair and maintenance make up some 40% of all construction work in the UK. A huge amount of investment is required on Repair and Maintenance costs in developing countries like India, Brazil, Chile, Peru, Thailand, Mexico and Nigeria. In fact, interest rate spreads have been widened in developing

countries, making it even harder to finance their Greenfield projects.
Advances in the measurement of rheological properties, mixing technology, aggregate handling for greater uniformity and cementitious materials blending will be key to improved concrete production. Durable concrete can be produced from carefully selecting materials to control and optimize their properties, reducing variability in the mixing, transport, placement, and curing of concrete. Understanding of the interaction between concrete and its environment is utmost important in concrete mix designs. The knowledge about the various causes is utmost essential to all engineers concerned prior to the concrete making.

II. CAUSES OF CONCRETE DISTRESS

Following are some of the causes of Concrete distress

1. Construction Deficiency (intrinsic)
2. Design Deficiency (intrinsic)
3. Environmental factors (extrinsic) and
4. Elevated Temperature (extrinsic)

2.1 Construction deficiency (intrinsic)

Construction deficiency involves both Physical and chemical factors.
Physical factors: Following are some of the physical factors of construction deficiency

1 Water Cement Ratio

The concept of water–cement ratio was developed by Duff A. Abrams and first published in 1918. It is the ratio of the weight of water to the weight of cement used in a concrete mix and has an important influence on the quality of concrete produced. Often, the water–cement ratio is characterized as the water to cement plus Pozzolana ratio, w/(c+p). The Pozzolana is typically a fly ash or blast furnace slag. It can include a number of other materials, such as silica fume, rice husk ash or natural Pozzolana. The addition of Pozzolana will influence the strength gain of the concrete

A lower water-cement ratio leads to higher strength and durability, but may make the mix more difficult to place. Placement difficulties can be resolved by using plasticizers or super-plasticizers. Too much water will result in segregation of the sand and aggregate components from the cement paste. Also, water that is not consumed by the hydration reaction may leave the concrete as it hardens, resulting in microscopic pores that will reduce the final strength of the concrete. A mix with too much water will experience more shrinkage as the excess water leaves, resulting in internal cracks and visible fractures (particularly around inside corners) which again will reduce the final strength which ultimately affects the durability. High capillary porosity in cement paste allows the aggressive chemicals from its environment to penetrate easily and the concrete as well as steel get affected at an accelerated rate and initiate the onset of corrosion. [13]

The corrosion of steel reinforcement is complex, but basically it is an electro-chemical reaction similar to that of a simple battery. The composition of mild steel varies along its length and potential anodic (more negatively charged) and cathodic (positively charged) sites can be set up at various points. It should be noted that in any discharging battery or galvanic cell, the anode is the negative terminal and the current flows into galvanic cell. In case of a recharging battery or an electrolytic cell, the anode is the positive terminal, which receives current from an external source.

Concrete is capable of conducting electric current and acts as the electrolyte with the circuit being completed by the bar through which the electrons can flow. However the highly alkaline environment (pH about 12.8) provided by good quality concrete produces a protective layer around the steel preventing the flow of current. This is known as Passivation**.** The corrosion reaction can only occur when there is a breakdown of the passivation layer (de-passivation) brought about by lowering of the alkalinity of the concrete below a critical pH of about 10.5, caused normally by the ingress of carbon dioxide (carbonation) or by the ingress of chlorides.

In a depassivation environment, the ferrous ions (Fe++) released from the anode combine with the hydroxyl ions (OH^-) from the cathode, in the presence of water and oxygen to produce rust (ferric hydroxide). This is an expansive reaction leading to eventual spalling of concrete cover and reduction in the area of the steel at the anodic site.

2 Curing

Curing is the process of controlling the rate and extent of moisture loss from concrete to ensure an uninterrupted hydration of Portland cement after concrete has been placed and finished in its final position. Curing also ensures to maintain an adequate temperature of concrete in its early ages, as this directly affects the rate of hydration of cement and eventually the strength gain of concrete or mortars. Following are a few reasons for which curing become essential.

a. Concrete strength gain

Concrete strength increases with age as moisture and a favorable temperature is present for hydration of cement. An experimental investigation was conducted by Cement, Concrete & Aggregates Australia (CCAA) and the same was published in their data sheet on Curing of Concrete. It was observed that concrete allowed to dry out immediately, achieves only 40% of the strength of the same concrete when water cured for the full period of 180 days.

b. Improved durability of concrete

The durability of concrete is affected by a number of factors including its permeability, porosity and sorptivity. Well cured concrete can minimize thermal, plastic & drying shrinkage cracks, making concrete more water tight, thus preventing moisture and water borne chemicals from entering into the concrete and thereby increasing its durability.

c. Enhanced serviceability

Concrete that is allowed to dry out quickly undergoes considerable early age shrinkage. Inadequate curing contributes to weak and dusty surfaces having a poor abrasion resistance.

d. Improved microstructure

Material properties are directly related to their microstructure. Curing assists the cement hydration reaction to progress steadily and develops calcium silicate hydrate gel, which binds the aggregates leading to a rocky solid mass, makes the concrete denser, decreases the porosity and enhances the physical and mechanical properties of concrete.

The chemical reactions between cement & water produces Calcium-Silicate-Hydrate (C-S-H) gel which bonds the ingredients of concrete, viz. coarse and fine aggregates, mineral admixtures, etc., and converts these fragments into a rock solid mass. This is possible only if continuous curing is done for at least 14 days, irrespective of the type of cement used. It is understood that blended cements require prolonged curing to convert calcium hydroxide into C-S-H gel. However, in case of Ordinary Portland Cement (OPC), voids within the concrete mass gets filled up and disconnected by the formation of C-S-H gel after about 10 days of curing. To have a dense microstructure and impermeability, prolonged curing is a must which leads to enhanced durability. Well designed concrete may give poor durability if not properly cured and on the other hand a moderately designed concrete if well cured can give a better durability. Hence importance of curing should never be ignored. Strictly adopting good curing practices at site will help concrete to achieve the properties of designed strength, enhanced durability, improved microstructure and a long lasting serviceability.

3 Aggregates

Aggregate in concrete is structural filler, but its role is more important than what that simple statement implies. Aggregate occupies most of the volume of the concrete. It is the stuff that the cement paste coats and binds together. The composition, shape, and size of the aggregate all have significant impact on the workability, durability, strength, weight, and shrinkage of the concrete. Aggregate can also influence the appearance of the cast surface.

Aggregate is classified as two different types, coarse and fine. Coarse aggregate is usually greater than 4.75mm, while fine aggregate is less than 4.75 mm. Most natural stones and crushed rock are appropriate for use in concrete. Commonly used stones are quartz, basalt, granite, marble, and limestone. Sources for these basic materials can be grouped into three main areas

a. Mining of mineral aggregate deposits, including sand, gravels and stone.
b. Use of waste slag from the manufacture of iron and steel and
c. Recycling of concrete. There are some materials such as clay, pumice, perlite, and vermiculite that are used for preparing lightweight aggregates.

Physical and mineralogical properties of aggregate must be known before mixing concrete to obtain a desirable mixture. These properties include shape and texture, size gradation, moisture content, specific gravity, reactivity, soundness and bulk unit weight. These properties along with the water/cementitious material ratio determine the strength, workability and durability of concrete. The shape and texture of aggregate affects the properties of fresh concrete more than hardened concrete. Concrete is more workable when smooth and rounded aggregate is used instead of rough angular or elongated aggregate. Most natural sands and gravel from riverbeds are smooth and rounded and are excellent aggregates. Crushed stone produces much more angular and elongated aggregates, which have a higher surface-to-volume ratio, better bond characteristics but require more cement paste to produce a workable mixture. The surface texture of aggregate can be either smooth or rough. A smooth surface can improve workability, yet a rougher surface generates a stronger bond between the paste and the aggregate creating a higher strength.

The grading or size distribution of aggregate is an important characteristic because it determines the paste requirement for workable concrete. This paste requirement is the factor controlling the cost, since cement is the most expensive component. It is therefore desirable to minimize the amount of paste consistent with the production of concrete that can be handled, compacted, and finished while providing the necessary strength and durability. The required amount of cement paste is dependent upon the amount of void space that must be filled and the total surface area that must be covered. When the particles are of uniform size the void spacing is the greatest, but when a range of sizes is used the void spaces are filled and the paste requirement is lowered. The more these voids are filled, the less workable the concrete becomes, therefore, a compromise between workability and economy is necessary. Well graded aggregate provides a denser concrete than poorly graded and gap graded aggregates. The denser the concrete, higher will be its strength and greater will be the durability. Poorly graded aggregates will create porous concrete due to presence of air voids which allows the aggressive chemicals from its environment to penetrate easily and the concrete as well as steel get affected at an accelerated rate and initiate the onset of corrosion

4. Compaction

Compaction is a process of expelling the entrapped air. If we don't expel this air, it will result into honeycombing and reduced strength. It has been found from the experimental studies that 1% air in the concrete approximately reduces the strength by 6%. Inadequate compaction will create porous concrete due to presence of air voids which allows the aggressive chemicals from its environment to penetrate easily and the concrete as well as steel get affected at an accelerated rate and initiate the onset of corrosion

5 Shuttering joints

Forms shall conform to the shapes, grades and dimensions including camber of the concrete as called for in the drawings. Ample studs, water braces, straps, shores etc. shall be used to hold the forms in proper position without any distortion whatsoever until the concrete has set sufficiently to permit removal for forms. Forms shall be strong enough to permit the use of immersion vibrators. In special cases, form vibrators may also be used. The shuttering shall be close boarded. Timber shall be well seasoned, free from sap, shakes, loose knots, worm holes, warps or other surface defects in contact with concrete. Faces coming in contact with concrete shall be free from adhering grout, plaster, paint, projecting nails, splits or other defects. Joints shall be sufficiently tight to prevent loss of water and fine material from concrete. [12]

When shuttering joints are not slurry tight, Honey combed concrete is created due to bleeding and the cement paste is replaced by air voids near surfaces and allows the aggressive chemicals to penetrate easily into the concrete.

6. Cover thicknesses

Cover is the certain thickness of concrete provided all round the steel bars to give adequate protection to steel against fire, corrosion and other harmful elements present in the atmosphere. It is measured as distance from the outer concrete surface to the nearest surface of steel. The amount of cover to be provided depends on the condition of exposure and shall be as per Nation's Code of Practice. The cover shall not be less than the diameter of the bar. The premature failure of corroded steel reinforcements and the expansion of the iron corrosion products around the rebars are amongst the main causes of the concrete degradation. The steel is protected from oxidation by atmospheric oxygen by the high pH of concrete interstitial water. Iron bar surface is passivated as long as the pH value is higher than 10.5. Fresh cement water has a pH of about 13.5 while evolved cement water, pH of 12.5 is controlled by the dissolution of Calcium Hydroxide. Carbon Dioxide present in the air slowly diffuses through the concrete cover over the rebar and progressively reacts with the alkaline hydroxides (KOH, NaOH) and with Calcium Hydroxide leading to the carbonation of the hydrated cement paste. As a result, the pH of the cement drops and when its value is below 10.5, steel surface is no longer passivated and starts to corrode. A sufficient thickness of concrete cover is thus required in order to slow down the carbonation process towards the rebar.

Carbon Dioxide from air can react with the calcium hydroxide in concrete to form Calcium Carbonate. This process is called carbonation. Carbonation has two effects: it increases mechanical strength of concrete, but it also decreases alkalinity, which is essential for corrosion prevention of the reinforcement steel. For the latter reason, carbonation is an unwanted process in concrete chemistry.

7 Wrong Placement of Reinforcement

One important reason for placing the reinforcing steel properly is to achieve the right amount of concrete covers. Cover is one of the most important factors in protecting reinforcing steel from corrosion. What is important to remember is that the design of the structure is based on having the steel in the right place. Incorrect placement of reinforcing steel will lead to serious concrete structural failures.

Chemical factors: Following are some of the chemical factors of construction deficiency

1. Chloride ingress

Chloride will enter into concrete mix either through the construction water and or through the aggregates. In such cases depassivation of steel reinforcement takes place and local galvanic cells will be formed which in turn initiates the corrosion of the steel reinforcement. Chloride ions acts as current carrier in presence of water and causes localized corrosion of steel reinforcement.

2 Sulphate ingress

When sulphate is infested beyond permissible limits either through the construction water or through the aggregates, an expansive product called as Tetra Calcium Trialuminate Sulfate (C_4A_3S) is formed which in turn causes disintegration due to the creation of bursting forces within the concrete mass. It is a slow process.

3 Reactive aggregates

Aggregates containing amorphous silica or strained quartz when come in contact with alkali materials of cement, then an expansive gel is formed which in turn causes disintegration due to the creation of bursting forces within the concrete mass. It is a slow process.

2.2 Design Deficiency (intrinsic)

Following are the two design deficiencies.

1. Wrong assessment of design loads

Wrong assessment of design loads will lead to cracks, deflection and crushing of structural members which in turn allow the aggressive chemicals from its environment to penetrate easily and the concrete as well as steel get affected at an accelerated rate and initiate the onset of corrosion.

2. Shrinkage

Factors like shrinkage, thermal movement and behaviour of the structural member if not considered then it leads to shrinkage cracks. Any crack for that matter allow the aggressive chemicals from its environment to penetrate easily and the concrete as well as steel get affected at an accelerated rate and initiate the onset of corrosion. The shrinkages are of the following types. They are as follows

a. Drying shrinkage

It is defined as the contracting of a hardened concrete mixture due to the loss of capillary water. This shrinkage causes an increase in tensile stress, which may lead to cracking, internal warping and external deflection.

b. Plastic shrinkage

Cracks are formed in the surface of the concrete whilst it is still plastic, that is before it has set and begun to harden, although they may not become visible until sometime later. They are due to the too rapid loss of moisture from the surface of the concrete, e.g. during hot, dry and windy conditions.

c. Autogenous shrinkage

It is an important phenomenon in young concrete. At low water to cement ratios, less than about 0.42, all the water is rapidly drawn into the hydration process and the demand for more water creates very fine capillaries. The surface tension within the capillaries cause Autogenous shrinkage, sometimes called chemical shrinkage or self-desiccation which can lead to cracking.

d. Carbonation shrinkage

It occurs where carbon dioxide penetrates beyond the surface of the concrete. This also depends on the moisture content and the humidity levels. Carbonation shrinkage is caused by the disbanding of Calcium Hydroxide crystals and the evidence of calcium carbonate.

2.3. Environmental factors (extrinsic)

Environmental factors are also categorised into two groups such as physical effects and chemical attacks.

Physical factors: Following are some of the physical agents associated with Environmental factors

1 Heating and Cooling

On account of continuous heating and cooling of the concrete, micro cracking and surface disintegration takes place. These cracks allow the aggressive chemicals and affect the concrete or reinforcement.

2 Wetting and drying

Alternate wetting and drying leads to increased capillary porosity of the concrete. Leaching away of water soluble salts results in depletion of water soluble Calcium Hydroxide which further reduces the alkalinity of the concrete. Once the alkalinity of the concrete reduces, it leads to initiation of steel corrosion in the absence of Calcium Hydroxide.

3 Abrasion of surfaces

Surface abrasion leads to disintegration and the reduced cover thickness. This will allow the aggressive chemicals to enter into the concrete and affects the concrete as well as steel.

4 Bacterial corrosion

Bacteria themselves do not have noticeable effect on concrete. However, sulfate-reducing bacteria in untreated sewage tend to produce hydrogen sulfide, which is then oxidized by aerobic bacteria present in biofilm on the concrete surface above the water level to sulfuric acid. The sulfuric acid dissolves the carbonates in the cured cement and causes strength loss.

Chemical factors: Following are some of the chemical agents associated with Environmental factors

1 Chloride attack

Sullage of toilets, sea water, atmospheric gases and atmospheric acids contain considerable amount of chlorides. When this chloride ion, penetrate and reach reinforcement level, causes local depassivation of steel and forms galvanic cells and initiate the corrosion

2 Sulphate attack

Soil, subsoil water, industrial wastes, industrial gases and acids contain considerable amount of sulphates. These sulphate ions react with Calcium Aluminates Hydrate (C-A-H) in cement paste and produce an expansive compound, which exerts bursting pressure to cause disintegration and cracking of concrete up to depth of permeation. Then the aggressive chemicals from its environment penetrate easily and the concrete as well as steel get affected at an accelerated rate and initiate the onset of corrosion.

2.4 Elevated Temperature (extrinsic)

If concrete is exposed to very high temperatures very rapidly, explosive spalling of the concrete can result. In a very hot, very quick fire the water inside the concrete will boil before it evaporates. The steam inside the concrete exerts expansive pressure and can initiate and forcibly expel a spall.

III. STAGES OF CONCRETE DISTRESS

There are two stages of concrete distress. Firstly, we have Initial damage stage of Reinforced Cement Concrete (RCC) and secondly, there will be Accelerated damage stage of RCC. In the first stage, the porous concrete allows the water and other aggressive chemicals to penetrate easily into the concrete and initiates the depassivation of steel. Later on, in the second stage an expansive compound is gradually created and it exerts a bursting force within the concrete. The bursting force causes cracks and leads to disintegration of the concrete.

IV. ECC AND ITS DURABILITY

The complex network of roads, bridges, railways, airports and canals serves as the backbone of global industry by moving both freight and people around the world in an efficient and convenient manner. Yet while all recognize its necessity, a serious commitment to maintaining these vital systems in developed nations is waning. American Society of Civil Engineers (ASCE) recently released updated 2005 grades of C and D for America's bridges and roads respectively. ASCE cited that to repair all deficient bridges it will cost in excess of US$ 180 billion over the next 20 years. Such problems are also evident in Australia where road and bridge conditions were assigned an average grade of C. to solve the serious challenges confronting global infrastructure, a fundamental solution reducing the brittle nature of concrete is needed. Engineered Cementitious Composites (ECC) addresses many of these current needs of infrastructure designers for an alternative to brittle concrete materials.

ECC represents a special kind of high performance fiber reinforced cementitious composite featuring high tensile ductility. Unlike concrete and conventional fiber-reinforced concrete (FRC) which shows unloading after matrix first cracking, ECC exhibits tensile-strain hardening behaviour achieved by sequential development of matrix multiple cracking. The tensile ductility of ECC is several hundred times that of normal concrete and crack width in ECC is self controlled and reaches a constant value (~60μm) after 1% elongation. It has been reported that ECC has lower water permeability and lower effective chloride diffusivity in the presence of micro-cracks when compared with cracked concrete in which the crack width is not self controlled and is usually in the range of several hundred micrometer to several millimeter. [11]

One of the most damaging environmental conditions to concrete is cyclic freezing and thawing. M. D. Lepech and V. C. Li conducted testing on freeze thaw exposure of ECC and concrete prisms concurrently over 14 weeks. After 5 weeks (110 cycles), the concrete specimens were severely deteriorated. However, all ECC specimens survived 300 cycles with no degradation of dynamic modulus. [1]

An increased problem in the United States is the maintenance and rehabilitation of the infrastructure. Deteriorations occur more rapidly in northern regions because of the cold weather in winter. It is well known that the widespread uses of de-icing salts during winter is one of the major causes of the rapid degradation of concrete pavements, bridge decks, parking structures and similar structures. When a de-icing salt is applied under freezing and thawing cycles on concrete structures, the destructive phenomena of scaling, cracking and other erosive effects will occur in the surface layer of concrete structures.

A study conducted by Mustafa Sahmaran and Victor C. Li reveals that the tensile strain capacity of virgin and pre-cracked specimens exposed to de-icing salts under freezing and thawing cycles range from 2.91% to 3.95%. The exposed ECC specimens retained at least the strain capacity of the ECC specimens unexposed to freezing and thawing cycles in the presence of de-icing salt. The virgin ECC specimens showed good performance when exposed to freezing and thawing cycles in the presence of de-icing salts and even after 50 cycles, a maximum of only 0.4 kg/m^2 of scaled-off particles were measured. An ECC is considered to be durable if the total mass of scaling residue is below 1 kg/m^2 after 50 freezing and thawing cycles (as per ASTM C 672). [2]

The corrosion of steel in concrete is one of the major problems with respect to the durability of the reinforced concrete structures. The penetration of chloride ions into concrete is considered to be the major cause of corrosion. A study, conducted by Mustafa Sahmaran et.al reveals that ECC is effective in slowing the diffusion of the chloride ion under combined and environmental (chloride exposure) loading by virtue of its ability to achieve self controlled tight crack width. [3]

Mustafa Sahmaran et.al in their study on durability of concrete subjected to highly alkaline environments (1N NaOH Solution) explained that the reloaded specimens (specimens which were pre-loaded under Uniaxial tension to different strain levels and then exposed to an alkaline environment up to 3 months at 38ºC and reloaded up to failure) showed slight loss of ductility and tensile strength but retained the multiple micro-cracking behaviour and tensile strain capacity of 2%. The test results indicated strong evidence of self healing of the micro-cracked ECC material. [4]

Michael D. Lepech says that the material durability plays a central role in sustainable concrete infrastructure. Therefore, adverse effects of industrial wastes on durability should be controlled. ECC was identified as the alternative material with the overall goal of improving sustainability. ECC materials are highly durable in a number of harsh environments. This durability results from unique pseudo strain-hardening ductility and distributed microcracking behaviour in tension. [5]

Yangzi Yang et.al, in their study have concluded that

1. Four to five cycles of wet-dry conditioning are necessary to attain the full benefit of self healing.
2. Self-healing in specimens subjected to a tensile strain of 0.3% and 3.0% brought the resonance frequencies back to 100% and 76% of initial values respectively. This exhibits the relation between the extent of self healing within the cracked ECC specimens and the level of strain damage to which they have been subjected to.
3. ECC specimens subjected to pre-load straining of a high level, even up to 2% or 3% after self healing, the tensile ductility character of ECC is retained. The self-healed ECC material remains ductile. [6]

It has been reported by Michael D. Lepech and Victor C. Li that the tight crack width in ECC are possible by using micromechanics as a tool for designing low permeability ECC composites which meet the two critical criteria of forming multiple cracks under load and ensuring that the maximum of fiber bridging stress verses crack opening relationship (σ-δ) for the composite occur below a crack width opening of 100µm. This relationship can also be used as a guide for tailoring the fiber, matrix and fiber/matrix interface within the composite to meet the low permeability criteria. [7]

ECC mixtures will have a tendency to undergo early-age cracking, which is a consequence of increased Autogenous shrinkage. It has been reported by Mustafa Sahmaran that fiber bridging stress verses crack opening relationship (σ-δ) at early ages will not be developed to withstand internal stresses caused by the external and internal restraints. Thus, insufficient tensile strain and Autogenous deformation may lead to the formation of some microcracks of the order greater than 100µm. while this cracking may or may not compromise with the mechanical properties of the composite, it may affect their long term durability. Traditional external curing techniques are not effective in eliminating early age cracking, since the water transportation into the ECC is hindered by the tightness of the matrix. In order to overcome this problem, use of pre-soaked lightweight aggregate (LWA) as internal water reservoirs has shown satisfactory results. Internal curing by means of pre-soaked LWA has been proved to be effective in reducing Autogenous shrinkage in high performance concrete with a low water-to-cement ratio. [8]

From the results of the study made by Mustafa Sahmaran, it is concluded that the use of water repellent admixture further reduces the water sorptivity and absorption properties of cracked ECC to a level significantly lower than that of normal un-cracked concrete. [9]

Mo Li and Victor C. Li in their study revealed the ability of ECC to self-heal crack damage in a high chloride concentration environment. Similar to self healing behavior in a water environment, nearly complete recovery of material stiffness and tensile strain capacity due to self-healing was found in ECC that has been loaded up to 1.5% tensile strain and immersed in 3%Nacl solution for 30 days or more. [10]

V. EXPERIMENTAL STUDIES ON ECC

5.1 Material Design Methodology

In the world of Materials Engineering, raw ingredients are shaped into a composite material through processing. Traditionally, selection of raw ingredients is based on empiricism. In recent years, composite materials are systematically being designed. One such material is “Engineered Cementitious Composite” (ECC). Micromechanics can be a powerful tool to deliberately tailor the composite ingredients, such as fiber dimensions and surface coatings along with sand particle amount and size. In addition, knowledge of material processing and its effect on both fresh and hardened properties aid in composite design.

Ordinary Portland Cement 53 Grade, Natural river sand (IS Zone III), Polycarboxylate Ether (PCE) based Superplasticizer, Fly Ash (Class F) and Polyvinyl Alcohol fibers (diameter 38 microns, length 8mm and the tensile strength 1400 MPa) were used in the design of concrete mix. The specific or recommended guidelines are not available for the Fiber Reinforced Concrete Mix Design. Hence, the Ideal Mix Proportion given in the Literature of ECC was used in this study. Various trial mixes were tried to satisfy the workability property of the PVA concrete. High volume fly ash content, low water to binder ratio of 0.27 with a Superplasticizer dosage of 0.25 percent of cementitious material and an aspect ratio of PVA fiber equal to 210 has passed the requirements of deformability characteristics of ECC. These requirements have established a target for the tailoring process of materials.

Typical Mix	**Cement**	**Sand**	**Fly Ash**	**SP**	**Water**	**Fiber**	**FA/PC**	**W/B**
PVA Concrete (Kg / m³)	570	456	684	3.135	338.6	26	1.2	0.27
FA: Fly Ash, W/B: Water to Binder ratio, FA/PC: Fly Ash to Portland Cement								

Table 1 Mixture Properties of PVA Concrete

5.2 Compressive Strength Test

Compressive strength results are primarily used to determine that the concrete mixture as delivered on site meets the requirements of the specified strength. The specimens were subjected to compressive load in a CTM of capacity 2000 KN to know the compressive strength of the PVA concrete for various percentages of PVA fibers

5.3 Direct Tensile Strength Test

Tensile strength is a paramount property of concrete. It determines the load-bearing behavior of concrete structures because the compressive strength, which is usually taken as design parameter, depends also on the tensile strength. Un-reinforced concrete structures rely completely on the tensile strength. The same is true for durability aspects. Fig 1 shows the dimensions of the Tensile strength test specimen.

The Specimens were cured for 28 days and subjected to Uniaxial tensile tests with suitable steel grippers in an UTM (Universal Testing Machine) of capacity 1000 KN and under displacement control of 0.005mm/s to know the strain hardening behaviour of the PVA concrete and consequent development of micro cracks.

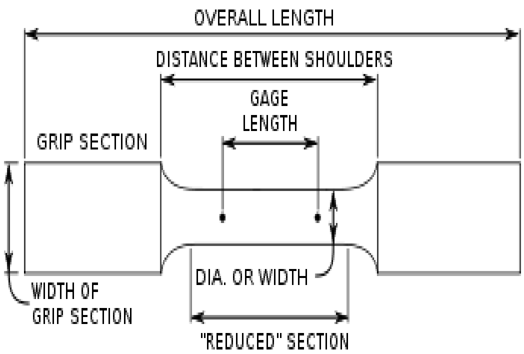

Fig 1 Tensile strength test specimen

5.4 Permeability Test

When concrete is permeable it can cause corrosion in reinforcement in presence of oxygen, moisture, CO_2, SO_3 and Chloride ions. The formation of rust due to corrosion becomes nearly 6 times the volume of original steel due to which cracking develops in reinforced concrete and spalling of concrete starts. So, if the concrete is made impermeable, the corrosion and ultimately spalling of concrete can be prevented.

150mm cubes were casted for the purpose of conducting the tests on permeability. The specimens were cured for 28 days and the cubes were subjected to a water pressure of 0.5 MPa on a surface of 100 mm diameter at the top of the specimen for a period of 72 hrs. The depth of penetration of water is measured by splitting the specimen in to two halves.

5.5 Rapid Chloride Penetration Test

The Rapid Chloride Penetration Test (RCPT) determines chloride permeability by measuring the number of coulombs able to pass through a sample. The RCPT consists of two parts: To obtain consistent chloride permeability values for a concrete batch each slice is conditioned to start at the same moisture content. Then the concrete is tested by measuring the charge passed through the slice when one side of the specimen is in contact with a Sodium Chloride (NaCl) solution and the other side is in contact with a Sodium Hydroxide (NaOH) solution. The current is recorded at 30 min intervals. The formula based on Trapezoidal Rule can be used to calculate the charge passed in Coulombs.

Charge passed = $Q = 900(I_0 + 2\ I_{30} + 2\ I_{60} + \ldots\ldots 2\ I_{300} + 2\ I_{330} + 2\ I_{360})$. Where,

I_0 = current immediately after voltage is applied in amperes

I_t = current at t min intervals after voltage is applied in amperes

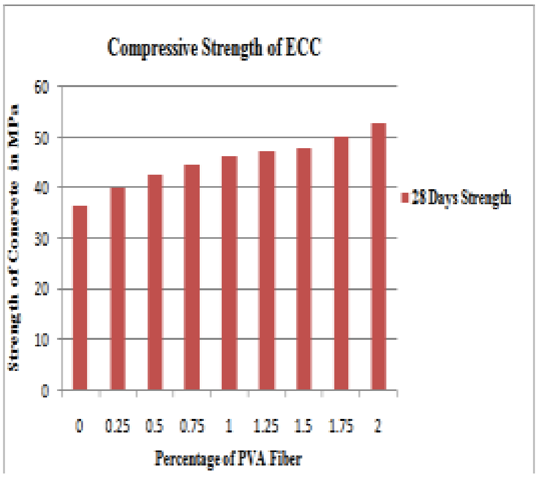

Fig 2 Strength of PVA Concrete

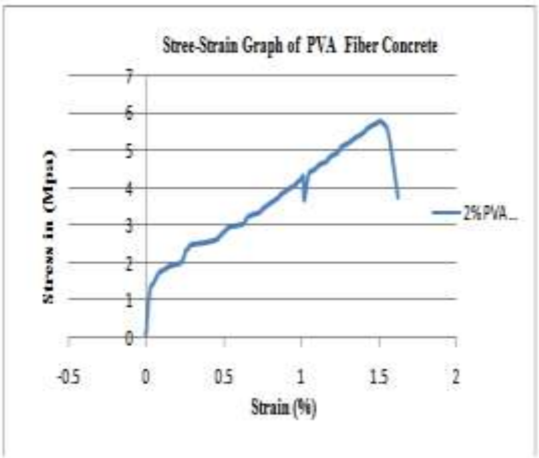

Fig 3 Stress-Strain Curve of PVA fiber Concrete

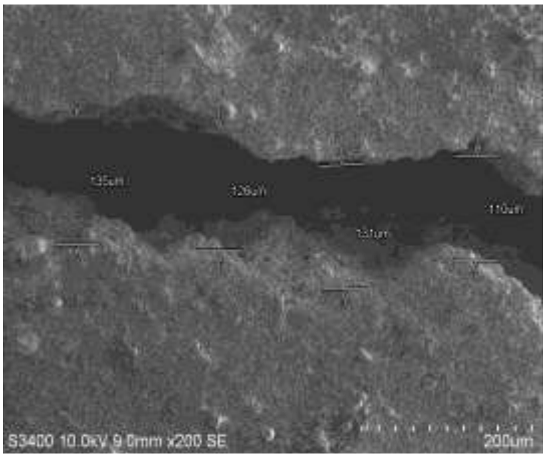

Fig 4 Crack Propagation of 2% PVA fiber Concrete at 2% strain
(Image captured through ESEM)

Fig 5 Permeated water Depth

VI. RESULTS AND CONCLUSION

The deterioration process of concrete can be considered in two different stages. During the first stage, on account of weathering effects and loading, the voids and microcracks developed in the interfacial zone will be gradually interlinked. Later on these interlinked networks of microcracks will get connected to cracks present at the concrete surface. This is how fluid transport mechanism takes place into the interior of the concrete. This is the stage where there will not be any noticeable change in the strength but some protective barrier is being broken down such as depassivation of steel by Carbon Dioxide or Chloride penetration. Further, permeability increases greatly and marks the second stage of deterioration in which, Water, Oxygen, Carbon Dioxide and Acidic ions are able to penetrate easily into the concrete. The concrete eventually undergoes increased cracking, spalling and loss of mass and ultimately reduces the strength as well as the durability of the concrete.

The ECC has a very high tensile ductility and a very tight crack width. ECC can be accepted as a virtually crack-free concrete and is expected to aid in extending the service life of concrete structures. Our civil infrastructure can be much smarter and ECC opens the door to potential applications where conventional concrete currently cannot be used.

Fig 2 represents the Bar chart which depicts the 28 days Compressive strengths of ECC. A Compressive Strength of 52.71 MPa (MegaPascal) has been attained for a fiber volume of 2 % at 28 days. Fig 3 represents a typical Stress-Strain Curve of PVA Fiber Reinforced Concrete. A Direct Tensile Strength of 5.8 MPa and a corresponding Strain of 1.51% have been achieved for a fiber volume of 2% at 28 days age. Fig 4 shows the Environmental Scanning Electronic Microscope (ESEM) image. The average crack width was found to be 125.5µm when strained to 1.51%. This shows that the PVA Concrete has a very good strain hardening behaviour when compared to Conventional Concrete which has a strain capacity of only 0.01%. Fig 5 reveals the depth of water permeated through 2 % PVA Concrete at the age of 28 days and is only 11.51mm which is less than the minimum cover to be provided in concrete elements. This shows the sign of durable concrete. The charge passed during RCPT test was 1458 Coulombs which indicates a low Chloride Ion Penetrability as per ASTM Standards. The Research work suggests the importance of ECC as an alternative material as far as Strength and Durability are concerned.

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