



GLOBAL JOURNAL OF RESEARCHES IN ENGINEERING: E  
CIVIL AND STRUCTURAL ENGINEERING  
Volume 23 Issue 4 Version 1.0 Year 2023  
Type: Double Blind Peer Reviewed International Research Journal  
Publisher: Global Journals  
Online ISSN: 2249-4596 & Print ISSN: 0975-5861

# Fundamentals of Electro Kinetics and Ionic Interactions for Durability Enhancement of Cement Concrete

By R. Selvaraj

*Introduction-* Durability of concrete structures is of great concern among civil engineering community. The concrete is one of the most widely used construction materials due to its relatively competitive affordability, versatility, easy availability of its raw materials, workability and mouldability to any shape and size. (1) Concrete is a composite material that consist of binding medium and aggregates particles. Once the concrete in set, it has three phases namely cement paste, the aggregate and the interfacial transition zone (ITZ) between them (2,3). The durability of cementitious materials is seriously affected by the service environments of the concrete. The service environment comprises several aggressive ions and are transported into the concrete through the pores, capillary pores, voids, cracks, microchannels, nanochannels and these ions react with the cementitious materials and as a result deterioration of concrete as well as embedded reinforcing steel is caused. Among these concrete defects, the capillary porosity and pores connectivity from the surface of concrete to the interior of concrete is of great concern from durability point of view. (4). Surface coatings or overlays on concrete can prevent entry of aggressive ions from environment to the concrete. However, the durability of coating or overlays are questionable.

*GJRE-E Classification:* LCC: TA439



*Strictly as per the compliance and regulations of:*



RESEARCH | DIVERSITY | ETHICS

# Fundamentals of Electro Kinetics and Ionic Interactions for Durability Enhancement of Cement Concrete

R. Selvaraj

## I. INTRODUCTION

Durability of concrete structures is of great concern among civil engineering community. The concrete is one of the most widely used construction materials due to its relatively competitive affordability, versatility, easy availability of its raw materials, workability and mouldability to any shape and size. (1) Concrete is a composite material that consist of binding medium and aggregates particles. Once the concrete in set, it has three phases namely cement paste, the aggregate and the interfacial transition zone (ITZ) between them (2,3). The durability of cementitious materials is seriously affected by the service environments of the concrete. The service environment comprises several aggressive ions and are transported into the concrete through the pores, capillary pores, voids, cracks, microchannels, nanochannels and these ions react with the cementitious materials and as a result deterioration of concrete as well as embedded reinforcing steel is caused. Among these concrete defects, the capillary porosity and pores connectivity from the surface of concrete to the interior of concrete is of great concern from durability point of view. (4). Surface coatings or overlays on concrete can prevent entry of aggressive ions from environment to the concrete. However, the durability of coating or overlays are questionable.

In recent years, the application of electrokinetic processes has been demonstrated to provide deeply penetrating metallic cations into the concrete from the surface of concrete and thus reduces the porosity to a greater extent. During the electrokinetic (EK) treatment, the charged nano particles (e.g., nano  $\text{SiO}_2$ ,  $\text{Ca}^{2+}$ ,  $\text{Na}^+$ , and  $\text{K}^+$ ) in ionic form are driven into the capillary pores and voids and block the pores. Some ionic species and particles react with the cement hydrates and precipitate and settle in the pores and this causes pore blocking and pore filling of concrete. This effect is greatly reduces the transport of nanoparticles and ionic species in to the concrete.

The electrokinetic technique was first reported in 1992 by Lageman (5). In the past decades, several researchers (6-10) have demonstrated deeply penetrating and highly effective porosity reduction using electrokinetic treatments applied to cement mortar and concrete. In one (10) study, by using alumina coated silica nanoparticles achieved electrokinetic porosity reduction as much as 57% in hardened cement paste. It is also reported (11-13) that them is an effective ionic transport into cement mortar and also significant reduction in corrosion of embedded steel reinforcement when ionic solutions and nano silica particles used in suspension.

## II. ELECTROKINETIC PHENOMENON

The movement of water through capillaries and pores of a porous medium with the application of electric field was first studied by F.F. Reuss in Russia in 1808 (14). This phenomenon was first treated analytically by Helmholtz in 1879, which was later modified by Pellet in 1903 and Smoluchowski in 1921. This phenomenon is widely known as the Helmholtz-Smoluchowski model, which relates electro-osmotic velocity of a fluid and charged porous medium under an electric gradient. The first application of electrokinetic was made by Casagrande in 1939 (14), for consolidating and stabilising soft fine-grained soils. Numerous laboratory studies and very few field applications have been conducted to investigate the electrokinetic processes till date. This electrokinetic technique has been applied successfully to same extent including increasing pile strength, stability of soil, removal of salts from the agricultural soils, removal of heavy metals from subsoils, removal of microorganisms which are causing damage to concrete sub structures in soil of low permeability, removal of contaminating chemical species from saturated and partially saturated porous soils, including removal of various inorganic and organic contaminants as shown in fig 1.

*Author: (Former Senior Principal Scientist at Central Electro Chemical Research Institute) C.E.C.R.I., Karaikudi, India.  
e-mail: selvarajcecri@gmail.com*

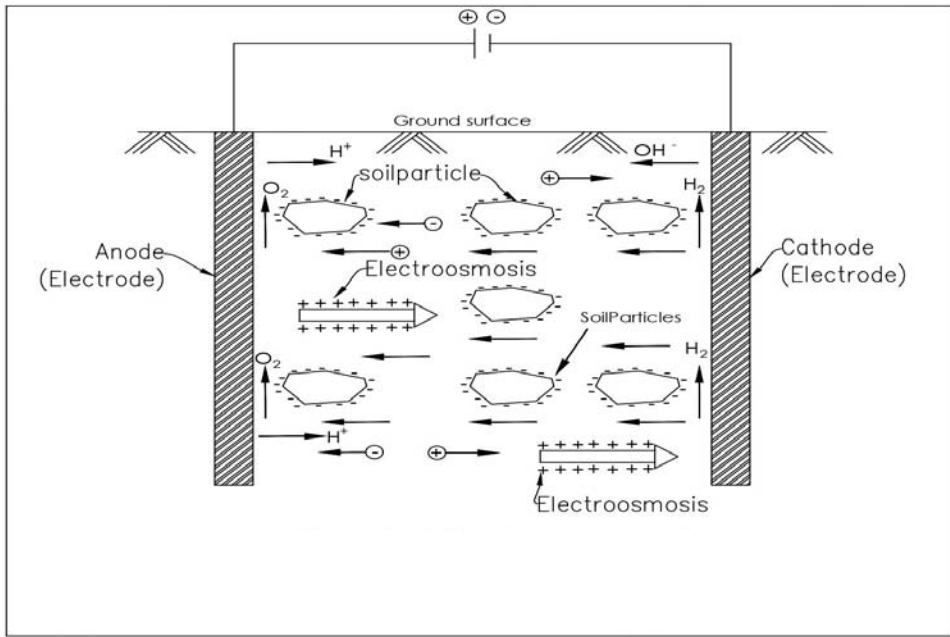


Fig. 1: Principles of Electrokinetic Transport in solurated porous Media (Ref. 15)

a) Principles of Electrokinetic: Transport Phenomena

Electrokinetic processes are relatively new and promising technology being investigated for their potential applications in hazardous waste management specifically in case of high clay containing soils (14).

United States Environmental Protection Agency (USEPA) has designated electrokinetic method as a viable in-situ process for decontaminating of low permeable soils. Electrokinetic process is neatly explained by the following fig 2.

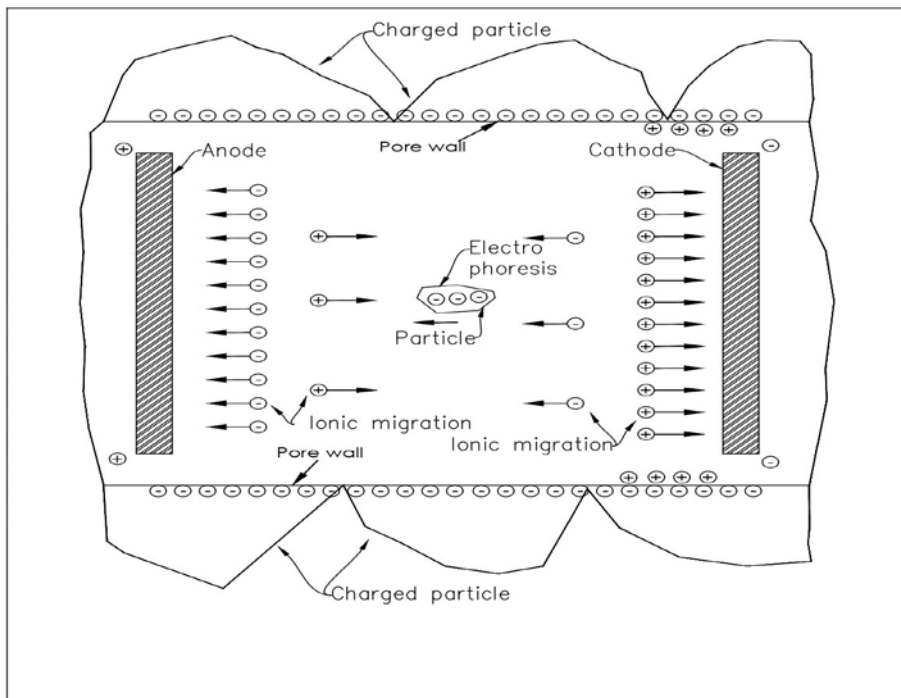


Fig. 2: Electrokinetics Electroosmasic, Electro phoresis and Electromigration is cement paste pores

The transport of ions and ionic species is induced in the pore solution on application of D.C. electric field, mainly by electromigration. This applied electric field induces water flow in a saturated porous

medium is called electroosmosis and there in possibility of movements of charged small particles in the pore solutions is called electrophoresis (16). The transported ions and particles in the capillary pores and voids react

with the hydrated cement pastes in the pore walls and converts into complex phases and thus settles in the pores and also attaches in the pore walls. This resulting complex salts blocks the pores and voids, therefore the permeability is greatly reduced. This pore blocking process in finally increases the compressive strength of the concrete. It also significantly prevents the ingress of aggressive ions from the immediate environment of the concrete and thus the durability and servicelife of the structure is greatly enhanced. (11-19)

i. *Electromigration*

Most of the porous materials carry a surface charge and have pores with presence of unbalanced charges with bound and unbound ions along the pore

wells (20). When an electric charge is applied the ions in the pore solution gets charged and is attracted by the oppositely charged electrodes and ions. Unlike in solutions, the ions in the porous materials are not able to move by electromigration directly to the opposite pole by the shortest route. Instead, they have to find their way along the tortuous pores. Presence of air-filled voids or particles filled voids block the direct path. The ions are normally transported in the continuous pores but not in the closed ones and the ions are transported in the pore solutions (21) fig 3 explains this pathways. The electromigration rate of a pores media depends on the pore volume, geometry of the pores and the water content.

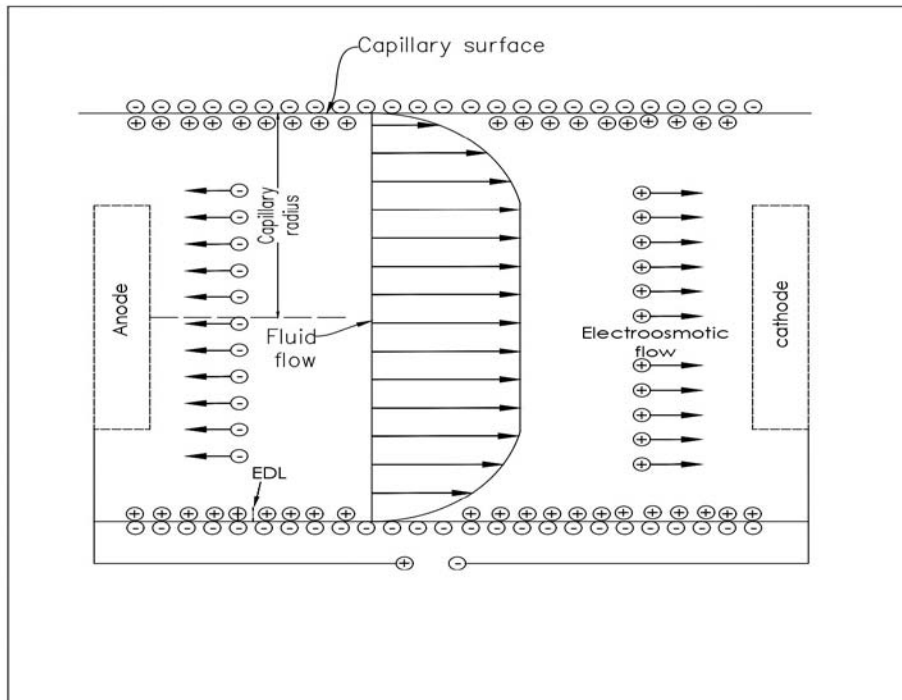


Fig. 3: Surface charges and Electroosmotic flow through pore

When DC electric field is applied across the electrodes in a saturated porous medium. The negatively charged ions migrate to anodes and positively charged cations move towards cathode. The classical theory of electro chemistry defines the flux due to electromigration is given by (22).

$$J = \frac{D_z E C T}{RT}$$

.....1

- Where J in the flux in (Kg/m<sup>2</sup>/s)
- Z is the valency of the ion
- F is the Faraday constant (96,485C moe<sup>-1</sup>)
- E in the applied electric field (Volt/m)
- R in the gas constant (8.3143 J moe<sup>-1</sup>K<sup>-1</sup>)
- T is the temperature (°K).

The fig 4 shows the positively and negatively charged particles and fig 5 shows the components of a charged particle.

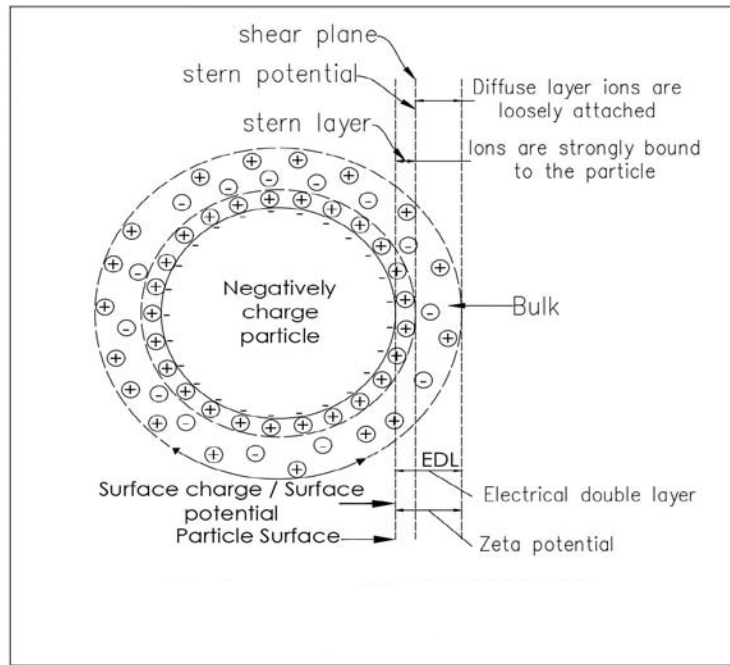


Fig. 4: Various components of a particle

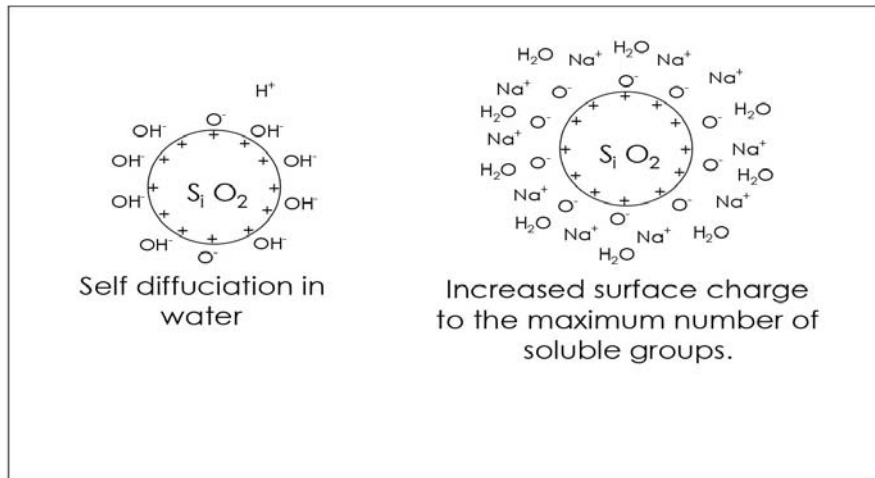


Fig. 5: Positively Charged Nano Particles

The ionic mobility of many cations falls in the range of  $1 \times 10^{-8}$  to  $10 \times 10^{-8}$  ( $m^2/Vs$ ) (23) Table 1 The movement of ions towards electrodes in the functions of ionic mobility (24-26) and the concentration of the electrolytic solution or the pore water. The ions travel with velocity given by (24).

When  $I$  is the applied current  
 $V_i$  is the ion velocity  
 $A$  is the area of cross section  
 $\rho_w$  in the pore water resistivity  
 $\tau$  is the tortuosity  
 $\theta$  is the volumetric moisture content

$$v = \frac{I v_i \rho_w}{A \tau \theta} \dots\dots\dots 2$$

The following table 1 presents the ionic mobility of selected ions in free electrolyte at 25°C (27).

Table 1: Ionic mobility of some selected ions in free electrolyte at 25°C (27)

Element	Ionic Mobility (10 <sup>-8</sup> m <sup>2</sup> /s)	Element	Ionic Mobility (10 <sup>-8</sup> m <sup>2</sup> /s)
H <sup>+</sup>	36.23	Na <sup>+</sup>	5.19
Al <sup>3+</sup>	6.32	Ph <sup>3+</sup>	7.36
Ca <sup>2+</sup>	6.17	Zn <sup>2+</sup>	5.47
Cd <sup>2+</sup>	7.36	OH <sup>-</sup>	20.6
Cr <sup>2+</sup>	6.94	Cl <sup>-</sup>	7.19
Ca <sup>2+</sup>	5.56	NO <sup>3-</sup>	7.40
Fe <sup>3+</sup>	5.60	SO <sub>4</sub> <sup>2-</sup>	8.29
K <sup>+</sup>	7.62	CO <sub>3</sub> <sup>2-</sup>	7.46

ii. *Electroosmosis*

Electroosmosis is the term given to the movement of the bulk aqueous solutions through the pores of a porous medium due to applied electric field. The electroosmosis was first observed in 1800s and was used in geotechnical engineering to clayey soils in 1930s (28). The electroosmotic effect is a result of the complex electrical interventions that exist at the interface between solid and liquid.

When the electric field applied across a saturated porous media, the ions in the pore fluid act as conducting medium and the movement of water is observed towards anode and cathode depending on overall surface charges of the porous material. The anions and cations will move towards opposite electrodes. The electroosmosis is significant in fine pores materials (29-32). It is important to note that in the most porous materials, the electroosmotic velocity is towards the cathode and the electroosmotic is enhancing the transport of cations towards the cathode. But the electromigration is the dominant mechanism (33). Several factors influence surface charge of cementitious materials and thus the electroosmotic effect.

Theoretically predicting electroosmotic flow becomes more difficult when the solid mass chemically reacts with pore water. The equation described as (34).

$$V_e = K_e i_e \dots\dots\dots 3$$

When  $V_e$  is electroosmotic velocity (L/T)  
 $K_e$  is electroosmotic Permeability (L<sup>2</sup>/VT)  
 and  $i_e$  is the potential gradient (V/L)

The  $K_e$ , the electroosmotic permeability of the medium is a function of dielectric constant of the medium, viscosity of pore water, zeta-potential and porosity of the medium. The  $K_e$  is given by (28)

$$K_e = \frac{\Sigma \epsilon n}{\mu} \dots\dots\dots 4$$

$\Sigma$  is the permittivity of the medium  
 $\epsilon$  is the Zeta potential  
 $n$  is the porosity and  
 $\mu$  is the liquid velocity

The fig shows various layers of the particle and represents the solid liquid interface and charge distribution in spore sections.

iii. *Electrophoresis*

Electrophoresis is the movement of charged particles (Colloidal Particles) present in the pore water on application of electric field. The mobility of the particle in functions of the Zeta protentional on the particle surface. The electrophoretic velocity of a particle was first described by Helmholtz and later refined by smoluchowski and is given by the relation.

$$V = \frac{\tau \epsilon E}{\mu} \dots\dots\dots 5$$

Where  $V$  is the particle Velocity  
 $E$  is the applied electric field  
 $\epsilon$  is the dielectric permittivity of the medium  
 $\mu$  is the viscosity of the pore fluid and  
 $\tau$  is the zeta potential of the particle surface

The electrophoretic mobility ( $\mu_e$ ) of a particle can also be defined as (35).

$$\mu_e = \frac{\Sigma \tau}{\mu} \dots\dots\dots 6$$

The mobility of colloids and particulates in porous medium also depends upon flocculation, sedimentation and depositions of particles in pores.

b) *Microstructural Properties of Concrete*

As has been stated earlier, the concrete is mixture of cement paste and aggregates. On a macroscopical scale the cement paste itself consist of unreacted cement grains, amorphous hydration product (Crystals of calcium hydroxide needles of ettringite and fibrous crystals of calcium silicate hydrates C-S-H) and pores (36). If pozzolanic materials are added to the



conventional concrete, the microstructure of concrete is modified by the pozzolanic reaction. Pore structure of the concrete is modified or densified homogeneity of the cement paste is improved porosity of cement paste is significantly reduced and thus it improves compressive strength of concrete. The pore connectivity determines the permeability and this parameter determines the transport properties of concrete or cement paste (37). Lesser permeability results durable concrete.

To achieve high strength and more durable concrete the capillary porosity shall be reduced and this can be achieved by reducing the gel porosity i.e. by changing C-S-H (Calcium silicate Hydrate) Structure from porous to more crystallize phase (micro structural change). This micro structural change in the cement paste greatly reduces the porosity reduced permeability and pore size distribution. The pores and the pore connectivity is shown in Fig. 6.

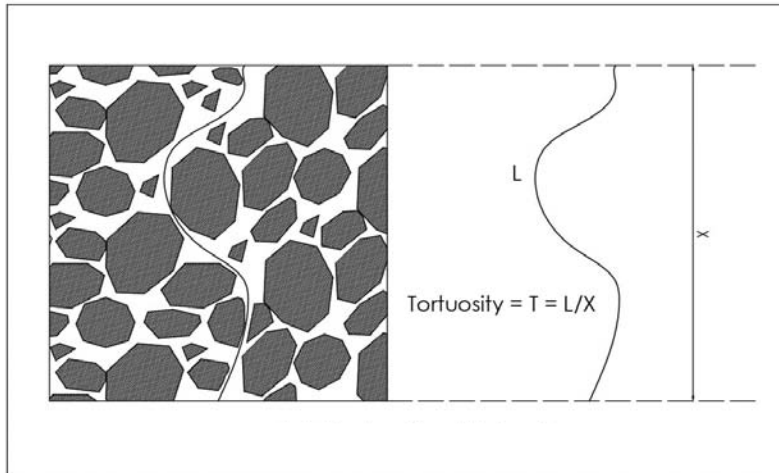


Fig. 6: Pictorial Explanation of Tortuosity

c) Calcium Silicate Hydrate (C-S-H)

When Portland Cement in mixed with water, anhydrous Oxides (Mainly CaO and SiO<sub>2</sub>) react with water and forms a solid and water in the pores. The solid part consists of Ca<sup>2+</sup>, OH<sup>-</sup> and silicate ions (38,39) When pore water gets more Ca<sup>2+</sup> ions, the P<sup>H</sup> of the pore water is increased more than 10 and it becomes super saturated. The main source of cohesion of cement paste is the nano particles of C-S-H, which is formed upon the dissolution of the original tricalcium

silicate (C<sub>3</sub>S) present in the cement. The Ca<sup>2+</sup> ions have strong physical affinity to negatively charged silicate particles. It should be noted that once the cement constituents are in contact with water, the constituent phases begin to dissolve at the surface of the grains, mainly C<sub>3</sub>S becomes negatively charged. The pore solution contains Ca<sup>2+</sup>, K<sup>+</sup>, Na<sup>+</sup>, OH<sup>-</sup>, SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> and SO<sub>4</sub><sup>-</sup> ions (40,41) and gets super saturated with respect to C-S-H (CaO-SiO<sub>2</sub>-H<sub>2</sub>O) = C-S-H.

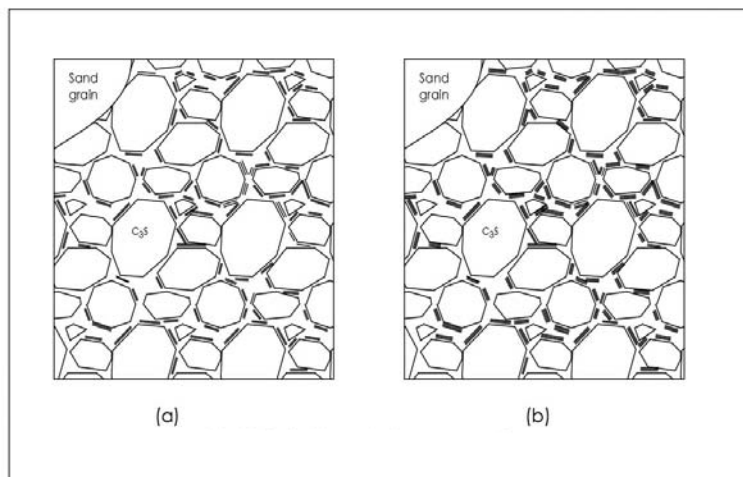


Fig. 7: Hydration of C<sub>3</sub>S component

The process of dissolution and precipitation continues. Initially the PH is increasing until the

precipitation of Calcium hydroxide occurs in the pore water. Among the precipitated hydrates in the pores, the





pore walls. This results in deposition of complex material in the pores and thus the density of the porous material is increased and the pore diameter is reduced significantly. This process of pore filling or pore blocking includes the strength, compactness and durability of the material (52-55). This pore filling material binds chemically in the pore spaces (see fig. 8). This pore filling treatment prevents ingress of aggressive species such as chlorides carbon di oxide and thus corrosion of

embedded steel is prevented. The finely divided cationic nano particles such as  $\text{Ca}^{2+}$ ,  $\text{Na}^+$   $\text{K}^+$  react with  $(\text{Ca}(\text{OH})_2)$  to form cementing hydrates and this enhances the strength (56,57) of concrete. A maximum current density of  $1\text{A}/\text{m}^2$  is continuously applied for a period of 6-12 weeks. The continuous generation of  $(\text{OH})^-$  ions assist in restoring the passivity of steel. Thus pore blocking treatment reduced the permeability by a factor of three.

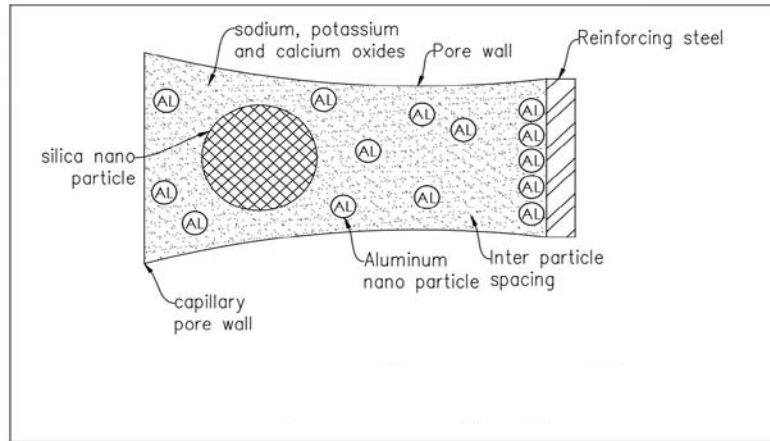


Fig. 8: Pore blocking: Positive nano particle and oxide deposits inside capillary pore

### III. CONCLUSION

1. The electrokinetic treatment is also applicable for removing the contaminants and heavy metals from the soil.
2. The formation of C-S-H improves tensile strength of concrete.
3. Pore blocking treatment blocks the pores voids cracks and all other defects by depositing complex salt in it. It reacts with pore walls and chemically binds. This results in compactness of concrete increases density, increases mechanical strengths by reducing porosity and pore connectivity.
4. Ingress of external aggressive agents like Chloride and  $\text{CO}_2$  in presented by pore blocking and thus corrosion of embedded steel in avoided and hence durability of concrete is increased significantly.

### REFERENCES RÉFÉRENCES REFERENCIAS

1. H. E. Cárdenas and H. Zhang, "Electrokinetic Nanoparticle Treatment: Success Factors," *Materials Science and Applications* (2020), p. 767-786.
2. P. K. Mehta and P. J. Monteiro, "Concrete: Microstructure, Properties, and Materials", 3rd ed., London, McGraw-Hill, 2006.
3. T. Akçaoglu, M. Tokyay, and T. Çelik, "Effect of Coarse Aggregate Type and Particle Quality on ITZ and Failure Behavior of Concrete Under Uniaxial Compression," *Cement and Concrete Composites* (2004), p. 633-638.
4. S. Minders and J. F. Young, (1996) 'Concrete', Prentice-Hall, Englewood Cliffs.
5. R. Lageman, "Electrokinetic Reclamation: Applications in the Netherlands," *Environmental Science & Technology* (1993), Vol. 27, p. 2648-2650.
6. H. Cárdenas, K. K. Patil, and S. Eklund, "Corrosion Mitigation in Matured Reinforced Concrete using Nanoscale Pozzolan Deposition," *Journal of Materials in Civil Engineering* (2011), Vol. 3, p. 752-760.
7. H. Cárdenas, K. K. Patil, and S. Eklund, "Recovery from Sulphate Attack in Cement via Electrokinetic Nanoparticle Treatment," *Journal of Materials in Civil Engineering* (2011), Vol. 1103-1112.
8. H. E. Cárdenas and L. I. Struble, "Electrokinetic Nanoparticle Treatment of Hardened Cement Paste for Reduction of Permeability," *Journal of Materials in Civil Engineering* (2006), Vol. 18, p. 554-560.
9. H. Cárdenas, J. Alexander, and K. K. Patil, "Field Testing of High Current Electrokinetic Nanoparticle Treatment for Corrosion Mitigation in Reinforced Concrete," *Second International Conference on Sustainable Cement Materials and Technologies* (2010), Ancona, 28-30 June.
10. J. Kanno, H. Richardson, J. Phillips, K. K. Patil, D. S. Mainardi, and H. E. Cárdenas, "Modeling and Simulation of Electromagnetic Processes for Multiscale Modification of Concrete," *Journal of Systemics, Cybernetics, and Informatics* (2009), Vol. 7, p. 69-74.

11. R. Mithra, R. Selvaraj, and O. M. Suganya, "Electrokinetic Technique for Enhancing Durability of Concrete," *International Journal of Civil Engineering and Technology* (2017), Vol. 8, p. 801-808.
12. R. Mithra, R. Selvaraj, and O. M. Suganya, "Applications of Electrokinetic Principles for Enhancing Durability of Concrete," *IOSR Journal of Mechanical and Civil Engineering* (2016), Vol. 13, p. 28-30.
13. S. Antony Sujina, R. Selvaraj, and B. Deepa, "Durability Enhancement of Cement Mortar by Using Electrokinetic Principles," *International Journal of Science and Research* (2010), Vol. 7, p. 1508-1514.
14. M. A. Karim, "Electrokinetics and Soil Decontamination: Concept and Overview," *Journal of Electrochemical Science and Engineering* (2014), DOI: 10.5599/Jese.2014.0054.
15. A. T. Yenng, "Contaminant Extractability by Electrokinetics," *Environmental Engineering Science* (2006), Vol. 23, p. 202-224.
16. L. M. Ottosen, I. V. Christensen, I. R. Dalgard, P. E. Jensen, and H. K. Hansen, "Utilization of Electromigration in Civil and Environmental Engineering: Processes, Transport Rates, and Matrix Changes," *Journal of Environmental Science and Health, Part A* (2008), Vol. 43, p. 745-809.
17. T. Matusinovic, J. Sipusic, and N. Vrbos, "Porosity-Strength Relations in Calcium Aluminate Cement Pastes," *Cement and Concrete Research* (2003), Vol. 33, p. 1801-1806.
18. M. Rosler and I. Odler, "Investigations on the Relationship between Porosity, Structure, and Strength of Hydrated Portland Cement Pastes," *Cement and Concrete Research* (1985), Vol. 15, pp. 320-330.
19. D. M. Roy and G. R. Gouda, "Porosity-Strength Relations in Cementitious Materials with High Strengths," *Journal of American Ceramic Society* (1973), Vol. 56, p. 549-550.
20. Marry, J. F. Dufreche, M. Jardat, G. Meriguet, P. Turq, and F. Grun, "Dynamics and Transport of Charged Porous Media," *Colloids and Surfaces A: Physicochemical and Engineering Aspects* (2003), Vol. 222, p. 147-153.
21. M. Saeem, S. E. Hussain, M. Maslehuddin, "Effects of Moisture, Chloride, and Sulfate Contamination on Electrical Resistivity of Portland Cement Concrete," *Construction and Building Materials* (1996).
22. P. Claisse and J. L. Marriaga, "The Effect of Other Ions on Chloride Migration in Concrete," Paper No. XX, 3rd International Conference on the Durability of Concrete Structures, 17-19 Sep. (2012), Queen's University, Belfast, p. 1-7.
23. A. T. Yenng, "Contaminant Extractability by Electrokinetics," *Environmental Engineering Science* (2006), Vol. 23, p. 202-224.
24. Vidya Ramalingam, "Electrokinetic Remediation," *The International Information Centre for Geotechnical Engineers*, U.S. Dept. of Energy, Online Manual (2013).
25. J. Virkulyte, "Electrokinetic Treatment Overview," *Science of the Total Environment* (2002).
26. H. D. Sharma and K. R. Reddy, "Geoenvironmental Engineering: Site Remediation, Waste Containment, and Emerging Waste Management Technologies", Wiley, Hoboken, N. J. (2004).
27. M. Amirthavarshni, R. Selvaraj, "Rudiments of Electrokinetic Method for Soil Remediation in Civil Engineering Perspective," *IJSR International Journal of Scientific Research* (2016), Vol. 5, p. 384-387.
28. R. Azzam and W. Oey, "The Utilization of Electrokinetics in Geotechnical and Environmental Engineering," *Transport in Porous Media* (2001), Vol. 42, p. 293-314.
29. H. K. Hansen, I. V. Kristensen, L. M. Ottosen, and A. Villumsen, "Electroosmotic Dewatering of Chalk, Sludge, Iron Hydroxide sludge, Wet Fly Ash, and Biomass Sludge," *Journal of Chemical Engineering in Japan* (2003), Vol. 36, p. 689-694.
30. L. M. Ottosen and R. Dalgard, "Drying Brick Masonry by Electroosmosis," *Proceedings of 7th International Masonry Conference, London, U.K.* (2006), p. 31-41.
31. J. Q. Shang, "Electrokinetic Dewatering of Clay Slurries as Engineered Soil Covers," *Canadian Geotechnical Journal* (1997), Vol. 34, p. 78-86.
32. S. Laursen, "Electrokinetics in Clays and Filter Cakes of Activated Sludges," *Water Science and Technology* (1993), Vol. 28, p. 181-188.
33. A. T. Yenng and J. K. Mitchell, "Coupled Fluid, Electrical, and Chemical Flows in Soil," *Geotechnique* (1993), Vol. 43, p. 121-134.
34. "The Use of Electrokinetics for Remediation of Contaminated Groundwater in Low Permeability Sediments," Honours Dissertation by Michael Gillon, October 2006, The University of Western Australia.
35. R. J. Hunter, "Foundations of Colloid Science", Oxford University Press, London.
36. K. M. Nemali, P. J. Monteiro, and K. I. Scrivener, "Analysis of Compressive Stress-Induced Cracks in Concrete," *ACI Materials Journal* (1998), Vol. 25, p. 617-630.
37. O. Buyukozturk and D. Lau, "High-Performance Concrete: Fundamentals and Applications", Cambridge Department of Civil and Environmental Engineering, Massachusetts Institute of Technology.
38. Nonat, "Materials and Structures" (1994), Vol. 27, p. 187.
39. S. P. Jiang, J. C. Mutin, and A. Nonat, "Cement and Concrete Research" (1995), Vol. 25, p. 779.
40. S. P. Jiang, J. C. Mutin, and A. Nonat, "Cement and Concrete Research" (1996), Vol. 26, p. 491.

41. L. Nachbaur, J. C. Mutin, A. Nonat, and L. Choplin, "Cement and Concrete Research" (2001), Vol. 31, p. 183.
42. B. O. Jonsson, A. Nonat, C. Labbez, B. Cabane, and H. Wennerstrom, "Controlling the Cohesion of Cement Paste," *Langmuir*, American Chemical Society (2005), p. A to K.
43. S. P. Jiang, C. J. Mulin and A. Nonat. *Cement and Concrete Research* (1996) Vol26, p491.
44. L. Nachbaur, J. C. Mutin, A. Nonat, and L. Choplin, "Cement and Concrete Research" (2001), Vol. 31, p. 183.
45. E. Samson, J. Marchand, and T. J. Beandoin, "Modeling the Influence of Chemical Reactions on the Mechanisms of Ionic Transport in Porous Materials," *Cement and Concrete Research* (2000), Vol. 30, pp. 1895-1902.
46. M. Ono, M. Nagashima, K. Otsuka, and T. Ito., "Mechanisms of Chemical Attack of Seawater in Cement Hydration" (in Japanese) (1978), Vol. 24, p. 100-103.
47. H. Souto, S. Nakane, Y. Tsuji, and A. Fujiwara, "Application of an Accelerated Electrochemical Test Method to Predict Degradation of Cement Hydration Products by Chemical Attack," *Journal of Materials in Concrete Structures and Pavements* (1997), Vol. 35, p. 189-197 (in Japanese).
48. H. Saito, Y. Tsuji, and H. Kataoka, "A Model for Predicting Degradation due to Dissolution of Cement Hydrate," *Transactions of the Japan Concrete Institute* (2000), Vol. 22, p. 119-130.
49. Y. Elakneswaran and T. Nawa, "Multi-Ionic Transport in Cementitious Materials with Non-Cement Hydrates Interactions."
50. H. Vialli-Terrisse, A. Nonat, and J. Petit, "Zeta Potential Study of Calcium Silicate Hydrates Interacting with Alkaline Cations," *Journal of Colloid and Interface Science* (2001), Vol. 244, p. 58-64.
51. C. Plassard et al., "Microscale Experimental Investigation of Particle Interactions at the Origin of the Cohesion of Cement," *Langmuir* (2005), Vol. 21, p. 7263-7270.
52. S. W. Morefield, V. F. Hock, C. A. Weiss, and P. G. Malone, "Application of Electrokinetic Nanoparticle Migration in the Production of Novel Concrete Composites," U.S. Army Engineer Research and Development Center, Geotechnical and Structures Laboratory, Vicksburg, MS. 39180.
53. T. Matusinovic, J. Sipusic, and N. Vrbos, "Porosity-Strength Relation in Calcium Aluminate Cement Pastes," *Cement and Concrete Research* (2003), Vol. 33, p. 1801-1806.
54. M. Roster and I. Odler, "Investigations on the Relationship between Porosity, Structure, and Strength of Hydrated Portland Cement Pastes," *Cement and Concrete Research* (1985), Vol. 15, p. 320-330.
55. D. M. Roy and G. R. Gouda, "Porosity-Strength Relation in Cementitious Materials with High Strengths," *Journal of the American Ceramic Society* (1973), Vol. 56, p. 549-550.
56. H. Cardenas and L. Struble, "Electrokinetic Nanoparticles Treatment of Hardened Cement Paste for Reduction of Permeability," *ASCE Journal of Materials in Civil Engineering* (2006), Vol. 18, p. 554-560.
57. H. Cardenas, "Investigation of Reactive Electrokinetic Processes for Permeability Reduction in Hardened Cement Paste," Ph.D. Thesis, University of Illinois, Urbana-Champaign.