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ELECTROKINETICS APPLICATION IN CONCRETE AND WELL CONSTRUCTION

Narjes Jafariesfad[1], Mette Rica Geiker, Sigbjørn Sangesland
Norwegian University of Science and Technology
Trondheim, Norway

Kamila Gawel, Malin Torsæter
SINTEF Industry
Trondheim, Norway

ABSTRACT

Electrically induced or coupled transport processes including electrophoresis, electroosmosis and electromigration in solutions and porous media under an external electric field have been extensively studied and employed in many disciplines.

For protection and rehabilitation of concrete structures, cathodic protection, electrochemical realkalization, and chloride extraction are extensively used. Other electrokinetic techniques are developed for the concrete industry, but have not been widely used so far, including electrokinetic treatment processes, for corrosion mitigation, recovery from sulfate attack, crack healing, and porosity and permeability reduction. These processes can improve the microstructure of the cement-based systems resulting in an improved performance in long-term and can be applied to repair failed structures.

Application of electrokinetic processes are rapidly extended in well construction due to the increased interest in techniques enabling manipulation of micro- and nanosized particles. The techniques could be beneficial in building a robust cement sheath in oil and gas wells. Additionally, electrokinetic remediation techniques can possibly be introduced for repairing damaged structures in oil and gas wells.

This review provides an overview of electrokinetic-based techniques, which has been introduced to cement-based materials, mainly reinforced concrete. The potential application of these techniques in oil well construction is discussed.

Keywords: Cement-based Materials; Electrokinetic Techniques; Well Construction; Electro-remediation; Concrete.

INTRODUCTION

Electrokinetic techniques are widely recognized as promising methods to manipulate transport of ionic species, and micro- and nanosized particles in porous structures [1-3]. These techniques are used in corrosion and protection processes [4, 5], environmental remediation [2, 6-8], upgrading of waste and removal/regain of heavy metals [9], biological systems [10, 11], and modification of cement-based materials [12]. Additionally, electrodeposition of coatings has gained a worldwide recognition in automotive and appliance industries [13]. Electrokinetic approaches have been used to introduce a variety of nanosized materials into porous substrates, which lead to changing properties of the structure [14]. This can provide relatively easy and cost-effective means to modify porous materials.

Cathodic protection of reinforced concrete structures is a well-established technique for mitigation of reinforcement corrosion, but also chloride extraction and realkalization are used for rehabilitation of reinforced concrete structures [5]. Recently, in concrete application field, additional electrokinetic-based techniques have gained attention. Cement-based systems can be exposed to controlled structural changes under external electric field as cement particles and ionic species present in pore solution are carrying electrical charge. Electrokinetics have been applied to enhance cement-based structures by corrosion mitigation [15, 16], recovery from sulfate attack [17], crack healing [18, 19], and porosity and permeability reduction [20, 21].

The electrokinetic methods used in concrete have the potential to be applied in well construction to provide a durable sealant for the whole life of the well or repairing failed structures. In this paper, application of electrokinetics in rendering concrete properties from fresh to hardened states are reviewed. The potential application of these methods in well construction/well cementing is discussed. And, the limitations that can affect electrokinetic application in well construction are discussed.

1. Electrokinetics

Electrokinetics comprises of three major processes: electrophoresis, electroosmosis and electromigration. An overview of the processes taking place under the application of an electric field is given in this section.

[1] Contact author: narjes.jafariesfad@ntnu.no

1.1. Electrophoresis

Electrophoresis is the movement of colloids or charged particles under the influence of an electric field (Figure 1). Under application of an electric field, charged particles suspended in a continuous phase are attracted toward the electrode of opposite charge. The particle velocity in an electric field, referred to as its electrophoretic mobility, depends on the strength of the electric field, the dielectric constant and viscosity of the medium, and the zeta potential and radius of the particle [22]. Charged particles in aqueous solution are surrounded by a cloud of counterions and the particle-counterion complex is electroneutral. The charge on the particle surface influences the ionic environment in the region close to the particle surface. A double layer model is typically used to describe the ionic environment; the stern layer, which is firmly attached to the particle surface, and the diffuse layer further away from the particle surface, but still attached to the particle. Within the diffuse layer there is a notional boundary, called slipping plane, inside which the ions and particles form a stable entity. When a particle moves, ions within the slipping plane move with it, but any ions beyond the slipping plane do not travel with the particle. Zeta potential, the main parameter determining the electrokinetic behavior of the particle, is the potential at the slipping plane, as shown in Figure 2. [22, 23]

Cement in an aqueous suspension reacts with water. The electrical double layer composition on cement is affected by hydration and vary with time [24]. This must be considered when determining and describing the zeta potential for hydrating cementitious materials. Nägele [25] has proposed three zones for cement zeta potential over time. In the first minutes (first zone) due to the vigorous initial reaction no zeta potential exists. In the second zone, about 5 minutes after the contact between cement and water, the non-equilibrium theory applies, and the zeta potential is time-dependent due to the chemical reactions. In the third zone (hardened cement), the reactions are so slow that equilibrium models can be applied, thus the hardened cement paste has a well-defined zeta potential [24]. In addition to the time-dependency of cement's zeta potential in aqueous suspensions [24, 26], the effect of admixtures [27-29], pH [30] and salts [31] is necessary to be considered.

1.2. Electroosmosis

Electroosmosis is the movement of a liquid relative to a stationary charged surface under the influence of an electric field. The electroosmosis phenomenon was described in 1952 by Casagrande who determined the law of water displacement in clay soil [6]. By applying an electric field, the ions in the mobile outer part of the electric double layer and water molecules attached to the ions move towards the electrode with the opposite sign. The inside parts of the double layer cannot participate in the movement. This movement results in the movement of pore water; and as water is displaced, it is replaced by more water being sucked into the pore [32].

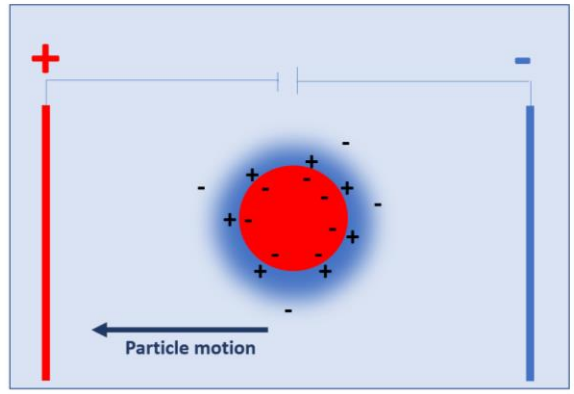

Figure 1: Electrophoretic movement of a charged particle in an aqueous solution with the application of electric field, after [32].

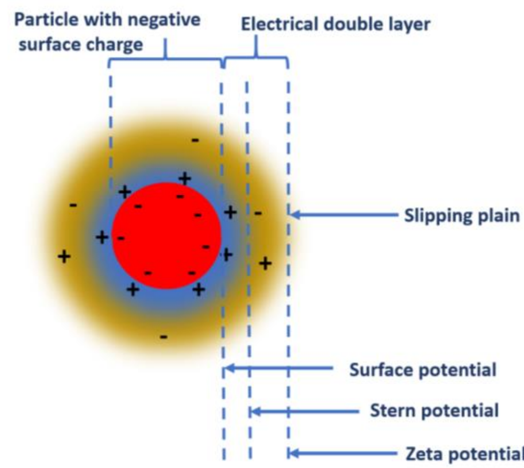

Figure 2: Schematic representation of the double layer surrounding a charged particle, after [22]. The zeta potential, the main parameter determining the electrokinetic behavior of the particle, is the potential at the slipping plane.

Electroosmotic velocity on a plane charged surface, U (m/s), can be calculated from the Helmholtz-Smoluchowski equation [7]:

$$U = -(\varepsilon \xi E_x)/\mu \quad (1)$$

where ε is the permittivity of the medium (C/Vm); ξ is zeta potential (V); E_x is the electric field strength (V/m) in a parallel direction to the electroosmotic flow; and μ is the medium viscosity (Ns/m^2). According to this equation, fluid flow is proportional to the electric filed strength and the zeta potential. With higher voltage, more water is displaced at both electrodes. The magnitude and sign of zeta potential depend on the interfacial chemistry, which is a complex function of the chemistry of both solid and liquid phases.

In the case of fresh cement suspensions, the electric double layer is essentially formed by electrically charged cement grains. After water-cement contact, the most soluble constituents of cement dissolve quickly and cause a rapid saturation of ions in solution. These ions and water molecules are then attracted by the charges of cement grains surface. Ions of the same sign as the surface's charge are repulsed while those of opposite sign are attracted, thereby forming a cloud of loads around the particle.

The combination of these charges forms the electrical double layer. By applying an electric field on fresh cement system, the cations and anions in pore solution would bring water with them and move together to corresponding electrode due to electrostatic attraction [33]. The quantities of water transported at anode and cathode increase with time and finally stabilize due to reduction of free water in fresh cement system. The displaced water at anode is lower than that at cathode, which could be attributed to different capacity of water carrying between cations and anions [33].

1.3. Electromigration

Electromigration is the movement of ions or ionic complexes in an applied electric field, which can be employed for supply or extraction of ions to/from porous materials [34, 35]. Electromigration is the mechanism causing chloride extraction from contaminated reinforced concrete. In general, electromigration has been applied for coatings, laminated or graded materials, and infiltration in porous structures.

The ion migration rate through a solution is determined by the electric field and the ions mobility, which depends on its charge, its hydrodynamic diameter, and the viscosity of the solution [36]. In the porous media, the rate of ion migration depends on the pore volume, geometry and the water content [34]. Table 1 presents the radius and mobility of some common ions in cement pore solution. Cations are generally less mobile than anions.

Table 1: Radii of some common ions in the pore solution and cement gel, data from [37], and ionic mobilities at infinite dilution in water at 298 K [36, 38]

Element	Radius (pm)	Mobility ($10^{-8}m^2s^{-1}V^{-1}$)
OH^-	137	20.64
O^{2-}	140	-
SO_4^{2-}	230	8.29
Ca^{2+}	100	6.17
Mg^{2+}	72	5.50
Al^{3+}	53.5	-
Na^+	-	5.20
Fe^{3+}	55	-
Fe^{2+}	61	-
K^+	138	7.62
H^+	1.2	36.23
Si^{4+}	40	-

2. Applications in Concrete

Electrokinetic methods can be applied in cement-based systems to change the system's properties on demand as an active control method [12]. Due to the hydration process, the conductivity of the paste changes with time. Initially, when in contact with water, cement starts to dissolve forming ions that act as charge carriers, leading to increase in conductivity. Later, by hydration acceleration, the pore volume decreases, which results in conductivity reduction. When an external electric field is applied to the fresh cement paste, a combination of particle, water and ion migration occurs. Depending on the field strength, duration and the application time, noticeable impact on chemical and mechanical properties and microstructure of the cement system can be observed [33, 39, 40]. Potential negative impact of electrochemical treatment of cement-based materials is further discussed in Section 4.

The conduction of electric current through a cement-based system can be divided into two components [41]:

- Liquid phase: Electronic conduction through the pore solution, which depends on ionic concentration, type of ions in the pore solution, and temperature.
- Solid phase: Electronic conduction through solid hydrates and unreacted cement grains. The solid phase conductivity is several orders of magnitude smaller than that of liquid phase.

The electrical conductivity of typical aggregates used in concrete are several orders of magnitude lower than that of the paste. Therefore, concrete can be considered as a composite of non-conductive particles contained in a conductive cement paste matrix. [42] In the cement paste, the electrical conduction is by means of ions in the pore solution, which are mainly OH^-, Na^+, and K^+, and in fresh paste also Ca^{2+} and SO_4^{2-} [42, 43]. The electrical properties of cement systems are time-dependent, which is changing with cement hydration process. At early ages, the pore water in the cement paste behaves like a semiconductor, but as hydration proceeds to completion, it becomes an insulator [44].

In the following section, application of electrokinetic processes in cement-based systems are reviewed. External electric field has been applied on fresh and hardened cementitious systems to modify their properties, from casting of concrete to mitigation of deterioration.

2.1. Electrochemical Treatment of Fresh and Young Concrete

2.1.1. Electric Curing

Electric curing was suggested more than 25 years ago by Bredenkamp et al. (1993). Electric curing of concrete is a process by which electric current is applied on the freshly poured concrete to accelerate the curing process by means of joule heating effect, thus increasing the initial rate of cement hydration [44]. During the cement hydration process, temperature rises due to the heat of cement hydration. Under an external electric field, the electrical energy, produced from current flow, converts to thermal energy. This results in additional temperature rise in the system, which has the potential to enhance the cement hydration rate, resulting in microstructural changes in the cement system [45, 46].

Susanto et al. [47] have investigated the impact of electrical current flow on cement hydration. Isothermal calorimetry was performed on cement paste with w/c ratio of 0.35 under DC current level of 10 mA/m^2, 100 mA/m^2, and 1 A/m^2. Figure 3 illustrates the rate of discharged heat over time, which increased with increasing the level of current flow.

The influence of current flow on the development of mechanical and electrical properties of fresh mortar samples (24 h cured) submerged in water, $Ca(OH)_2$ solution (Figure 4a), and not submerged ("sealed") conditions was studied by Susanto et al. [48, 49]. For water submerged samples, the direct current

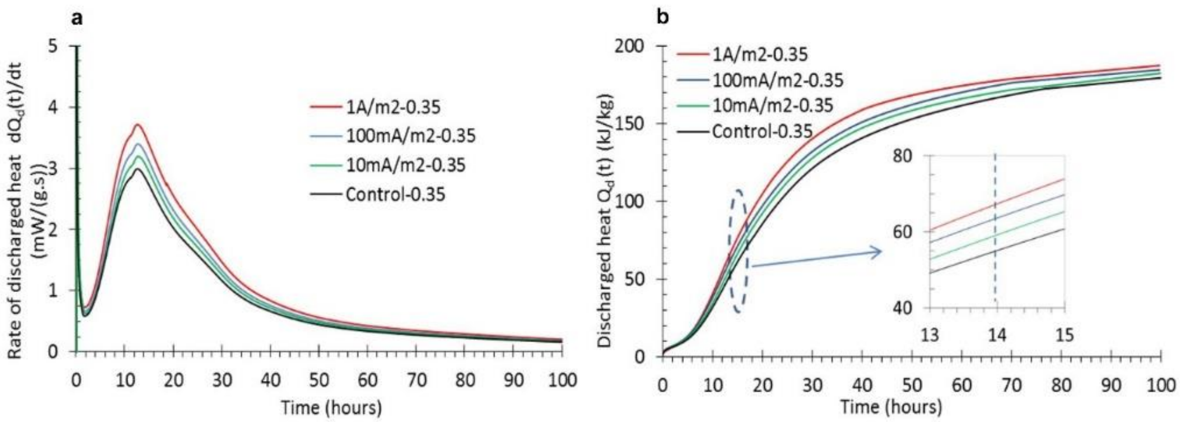

Figure 3: Impact of current flow level on hydration of cement paste with w/c ratio of 0.35 measured by isothermal calorimetry at 20 °C; a) rate of discharged heat, and b) cumulative amount of discharged heat [47].

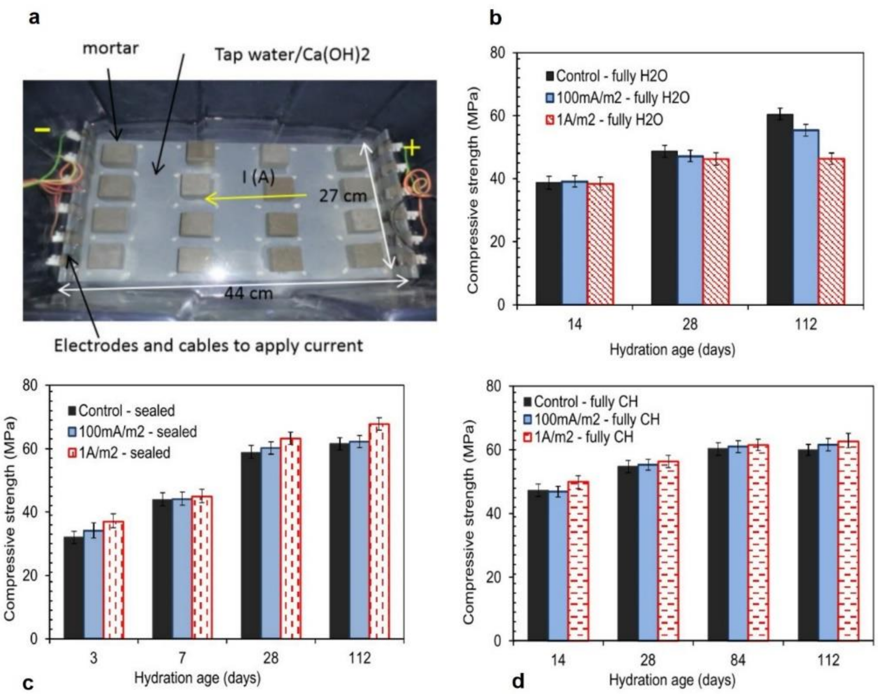

Figure 4: a) Experimental set-up for DC curing of samples submerged in water and $Ca(OH)_2$ solution [50]. Compressive strength as a function of curing time for mortar samples under current flow conditions: b) submerged in H_2O; c) sealed condition; d) submerged in $Ca(OH)_2$ solution [49].

application accelerated the degradation processes and decreased compressive strength (Figure 4b), reduced electrical resistivity and increased porosity were reported. This was attributed to the increased rate of leaching-out alkali ions by water and ions migration under applied current flow. In contrast, current flowing through sealed and samples submerged in alkaline medium resulted in increased compressive strength (Figures 4c and 4d) and electrical resistivity, and reduced porosity of the bulk matrix [49]. The authors concluded that application of current flow through cement-based systems at early ages, can lead to both positive and negative effects [49]. These effects are dependent on the external environment and the current density levels.

2.1.2. Demolding of Concrete Elements

Recently, electroosmosis was applied to facilitate demolding of concrete elements [40]. Instead of using release agent, application of an electric field on the mold after casting was used to induce migration of pore water toward the concrete-mold interface. The displaced water provides a water film that forms a separation screen between the concrete and the mold walls to ensure demolding. The quality of facing and demolding was shown to be dependent on the temperature and polarization parameters such as voltage value, time and duration of its application. The optimal polarization parameters in the process of electro-demolding are affected by the temperature [39]. This

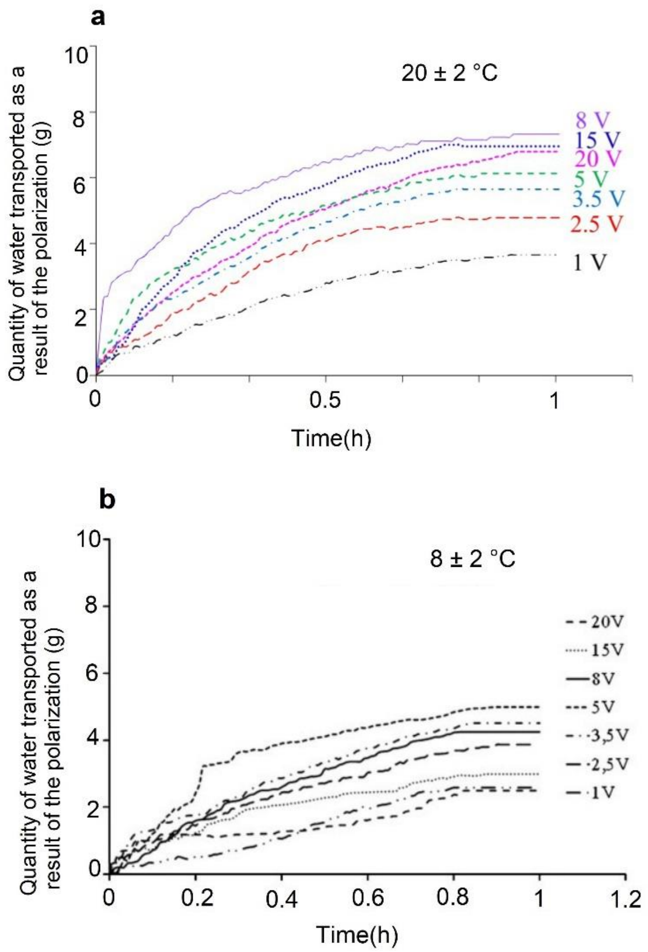

Figure 5: The quantity of transported water over time as a function of applied voltage at ambient temperature of: a) 20 ± 2 °C [40], and b) 8 ± 2 °C [39].

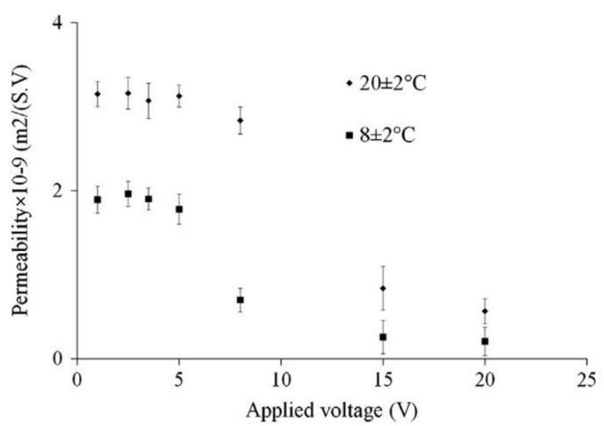

Figure 6: Electroosmotic permeability as a function of applied voltage [39].

is due to the temperature influence on the electric conductivity of the concrete and thus the amount of water transported to the interface, see Figure 5. At 20 ℃, it was demonstrated that by increasing the value of applied voltage up to 8 V, the amount of displaced water increased. For voltage values beyond 5 V, the number of ions and fine elements displaced is much more important. This could result in significant displacement of fine particles and thus cause a modification of the microstructure. The displacement of fine particles decreases the permeability coefficient (Figure 6) and therefore leads to a decrease in the amount of water being displaced [40]. In order to reach a good quality of demolding and facing, the quantity of transported water must be sufficient. Excessive water transport at the early stage would induce a raise of the w/c ratio at the concrete-mold interface, which alters the surface quality [39].

It should be noted that the applied voltage can affect the hydration process, pore structure and strength of the system, for more details please see [33].

2.1.3. Modification of Steel-Concrete Interface

The characteristics of the steel-concrete interface [51] affects the threshold for initiation of chloride induced corrosion [52]. Under some conditions, voids at the steel-concrete interface significantly reduces the chloride threshold [53, 54] , which led Buenfeld et al. [55] to suggest electrochemical treatment of the young concrete to manipulate the steel-concrete interface.

2.2. Electrokinetic Treatment of Hardened Concrete

Electrochemical remediation techniques are based on the accelerated transport of charged particles or ions inside pore structure under application of an electric field [21, 56]. Recently, electrokinetic nanoparticle (EN) treatment was introduced to improve the microstructure of concrete and upgrading the durability by blocking the concrete pores. Detailed information about EN treatment for different purposes is discussed in this section.

2.2.1. Mitigation of Reinforcement Corrosion

Forcing a direct current to circulate between the steel reinforcement and an external anode causes several principle reactions, see e.g. [5]:

1. The electrochemical potential of the steel reinforcement to reduce
2. Anions to move towards the external anode
3. Cations to move towards the steel reinforcement, especially sodium and potassium ions which the pore solution is rich in
4. Cathode reactions at the steel reinforcement, typically electrolysis of water resulting in hydroxyl ions, but also hydrogen evolution
5. Anode reactions at the steel, typically reduction of hydroxyl ions resulting in formation of oxygen and water.

Varying the duration and the field strength, these reactions are utilized for:

1. Preventing corrosion initiation or, if sufficiently low, protecting further corrosion
2. Extracting of chloride ions
3. Realkalization.

Especially, cathodic protection has become a well-established technique for mitigation of reinforcement corrosion in structures as marine bridges, where the environmental load is long-term and covering most of the structure. While cathodic prevention and protection are permanent (or at least long-term) treatments with application of relatively low current density (impressed or by sacrificial anodes), chloride extraction and realkaliszation are short-term treatments using relatively high current density. Electrochemical treatment of concrete has side effects in form of e.g. increased alkalinity at the reinforcement potentially causing alkali reactions of aggregates, loss of bond between steel and concrete, hydrogen embrittlement of steel and changes of the pore structure of the concrete. Potential side effects need to be considered if the concrete is planned to be exposed to external electric field.

Recently, temporary electrochemical treatment in connection with mechanical repair was proposed used for removal of chlorides from corrosion pits [57, 58]. Such "electro active repair" is foreseen to substantially increase the service life of mechanical repair, which is e.g. applied on diced structures with local damage.

Recently, the use of electric field to transport positively charged nanoparticles to the reinforcement ("EN treatment") while driving away the chloride ions was proposed by Cardenas et al. as a rapid repair technique to mitigate chloride induced corrosion of reinforcement in concrete [15, 16, 59, 60]. Electrokinetic injection of nanoscale pozzolanic admixtures has been applied to mitigate reinforcement corrosion in hardened concrete [16]. Initially, the treatment drew sodium, potassium, and calcium ions to the reinforcement surface, increasing the local alkalinity while driving away chlorides. Later, as the nanoparticles arrived, they were expected to react with available calcium to form a calcium-silicate-hydrate (C-S-H) barrier around the realkalized region. The technique was claimed to be successful in forming a chloride penetration barrier rapidly at field condition [16].

2.2.2. Reduction of Permeability/Upgrading Durability

Electrokinetic treatment has been applied to refine the pore structure, and thus reduce porosity/permeability and improve the durability of the cement-based systems [61]. Different solutions and colloidal systems have been used for electrokinetic treatment of cementitious structures. This treatment method seems to be promising in densification of cementitious structures and surface coating in order to upgrade their durability [62, 63].

In order to improve the durability of mortar, silicate ions were injected into mortar pores by applying an electric field [64, 65]. These ions react with calcium hydroxide to promote additional C-S-H gel formation, resulting in densification of the mortar [64]. Additionally, a surface coating was formed due to the calcium ions migration from the mortar pores to the sodium silicate solution. Electrokinetically treated mortar specimens presented reduced chloride diffusion coefficient by more than six times compared to the control specimen [64].

Xu et al. (2015) have reported surface coating treatment and densification of mortar using electrodeposition method. The coating layer had a uniform distribution with good adhesion to the mortar surface. The coating thickness was in the range of 0.2-1.1 mm and was dependent on applied voltage and its duration, concentration of solution, and temperature.[62].

Cardenas et al. (2006) have used EN treatment for injecting colloidal nanoparticles into hardened cement paste pores, where they would react with pore fluid ions to produce low-porosity phases, reducing permeability. EN treatment with alumina nanoparticles resulted in permeability reduction over an order of magnitude. Similar results were achieved using silica nanoparticles with the addition of calcium sulfate to accelerate the reaction rate. [20] The reduction in permeability was proposed to be due to the reaction of nanoparticles with calcium hydroxide in concrete and thus formation of C-S-H and calcium aluminate hydrates (C-A-H).

Electrokinetic surface coating was also proposed for protection of marble stone from the by-products of urban pollution and enhancement of its chemical and physical resistance in low-pH environments. A thick and homogenous layer of calcium oxalate formed on the stone surface due to the electrochemical reactions [66].

2.2.3. Closure of Cracks

When there are cracks in concrete, under applied external electric field, the electrical flow become enforced in the location of cracks. Therefore, the electrochemical deposition occurs mainly within the cracks, thus the cracks can be closed by the electrochemical deposition. In addition to crack closure, the electrochemical deposition technique was claimed to densify uncracked concrete, which upgrades its durability.

Electrochemical deposition technique was suggested used to repair concrete cracks in the marine environment or at other conditions, where traditional repair methods fail [67-70]. A recent paper [71] supports the use of temporary cathodic protection to limit early chloride ingress and at the same time facilitate self-healing of cracks. Electrochemical deposition was also suggested as a promising technique to repair internal concrete defects [72], and underground structures [73].

Effectiveness of electrodeposition technique in filling up cracks depends on the type of external solution and its concentration [74], the density of applied current, the stability of the intruding cation in local environment [71, 75], the concrete properties and the temperature [68]. The most effective solution for electrodeposition was suggested to be $ZnSO_4$ solution [74], the set-up of electrochemical deposition and the mechanism of crack closure by precipitation of ZnO are illustrated in Figure 7. Jiang et al. (2008) have used $Mg(NO_3)_2$ solution as electrolyte for electrochemical deposition of $Mg(OH)_2$ for rehabilitation of cracks in reinforced concrete. The electrodeposition rate was dependent on the current density and concentration of electrolyte [18]. The current density and concentration of electrolyte solution affected the morphology of the material deposited in the cracks [18, 19].

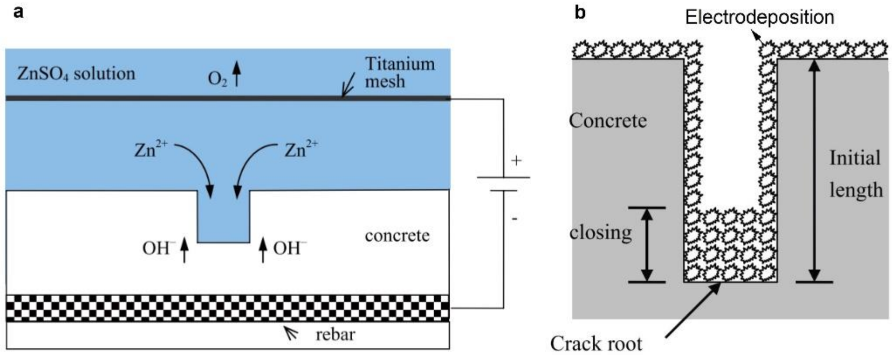

Figure 7: Suggested mechanism of electrodeposition of ZnO from $ZnSO_4$ solution. Schematic illustration of: a) the set-up ; and b) the deposition mechanism, which starts from the root of the crack and piles up to the surface. [67]

2.2.4. Improving Bonding Strength

Electrokinetic treatment has been applied for improving the bonding strength between the steel reinforcement and concrete. Wu et. al (2016) investigated the application of nanoalumina suspension as anolyte for EN treatment of reinforced concrete. An external electric current (current density of 3 A/m^2, for duration of 3 and 15 days) was applied to reinforced concrete blocks toward steel reinforcement to drift nanoalumina into concrete pores. The observation of the morphology of the specimen cross-section evidenced transport of nanoalumina from the exposure surface reaching the rebar-concrete interface. Electrokinetic treatment for 15 days and current densities up to 1.5 A/m^2, the bond strength of rebar-concrete interface increased considerably. [56]

2.2.5. Prevention and Recovery from Chemical and Biological Attack

Cardenas et al. (2011) investigated the recovery from sulfate attack in concrete via EN treatment. They introduced a new repair strategy that implements sulfate extraction concurrent with the injection of alumina-coated-silica nanoparticles for mitigating the microstructural damage resulting from a sulfate attack. Treated specimens had lower sulfate content and a higher C-S-H, exhibited a 40 % reduction in threshold pore size, and also showed a 33 % increase in compressive strength while the porosity decreased by one-third. [17]

Electrokinetics was also used to prevent microbiologically induced concrete degradation, which is a deterioration mechanism acting in concrete wastewater conveyance systems [35]. Chemical reactions between the hydration products in the hardened cement paste and biologically produced sulfuric acid changes the chemical composition of cement binder leading to early deterioration and loss of strength. An antimicrobial agent (cuprous oxide) can be driven into the porous surface of a pre-cast concrete structure by applying a potential difference between the steel reinforcement and a copper electrode placed in the coating solution. This results in breaking the MIC cycle by preventing colonization of the bacteria, which converts hydrogen sulfide to sulfuric acid. [35]

3. Applications in Well Construction

In oil and gas industry, a number of patents have introduced electrokinetics to drilling process [76-79], cementing [80], and hydraulic fracturing [81]. More so can be implemented to well construction from the lessons learned in other areas especially concrete industry.

3.1. Improved Cementing Process

Kolaian and Park (1968) applied DC potential to the casing to force the solid particles in the drilling fluid migrate away from the casing surface by electrophoresis and the water migrate toward the casing by electroosmosis. This resulted in a clean and water wet surface to be cemented. Figure 8a demonstrates application of negative voltage to the casing prior to introduction of cement slurry around the casing, considering that the particles in drilling fluid are negatively charged. This causes the particles to be repelled from the casing surface. In the case of employing a drilling fluid with positively charged particles, positive voltage needs to be applied [80]. Later, during cementing process, the application of positive potential at casing, resulting in migration of cement particles in the slurry toward the casing as the cement particles are negatively charged. This was claimed to assure presence of sufficient cement ingredients at casing interface to provide a good seal. In order to prevent water electrolysis and thus gas formation, application of voltages below 2 V was suggested [80]. Lavrov et al. (2016) have also applied DC voltage to increase the cement-steel adhesion at the positive electrode [82]. The cement-steel interface at anode and cathode was affected by voltage application [83]. Further research is essential to investigate microstructural changes of cement system under external electric field, and thus determination of optimal parameters for positive effect.

3.2. Repair of Damaged Cement Sheath

Nemecek et al. (2017) have proposed electrokinetic injection of nanoparticles into hardened cement in order to repair the leak paths within the cement sheath. They have investigated the efficiency of nanosilica and nanoalumina for electrokinetic remediation of cracked cement samples. Decreased overall porosity and pore sealing was noticeable on the cracked samples [84]. In order to reach a good microstructure refinement and mechanical performance, the repair particles need to have less

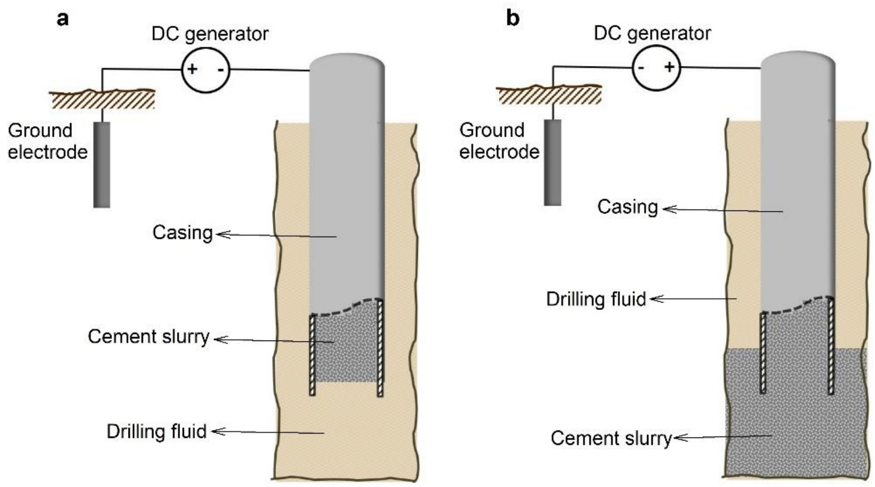

Fig. 8: Schematic view of the well showing the apparatus for: a) cleaning the casing from the drilling mud; b) increasing the bonding of cement to casing by DC field application, after [80].

stiffness than the aged cement paste and appropriate particle size [85]. If not, they might encourage the crack propagation due to the stress concentration at stiff incorporated particles, decreasing toughness of the cement system [85].

3.3. Improved Pumping

Electrorheological fluids are one of the most interesting smart materials, which have electro-responsive rheology. In drilling process, pumpability of the drilling fluid and its rheology are playing a key role. When drilling or completion fluid has a high viscosity, higher pumping pressure is required which can overcome the fracture gradient of the formation causing fracturing and wellbore instability. In a method for drilling oil and gas wells, in order to control mud rheology, electrorheological fluid has been introduced [77, 79, 86]. The viscosity of this fluid can be controlled by applying, increasing, decreasing or removing an electric field to the fluid. Controlling the viscosity of cement slurry is also an important parameter, which affects cementing process quality and cement placement. Possibility of controlling the flow of cement slurry by external means could be helpful in providing a cost-effective and good cementing job. In concrete area, electromagnetic field has been used to control the pumpability of concrete [87]. An electromagnetic field was applied to manipulate and control the properties of the lubrication layer formed on the wall of the pipe. Formation of a lubrication layer is the main factor improving the pumpability of the concrete, which is due to its noticeably lower viscosity and yield stress compared to the concrete [87]. Under applied electromagnetic field, the same flow rate conditions were obtained with a 30 % reduction in the pump pressure. Under the same pump pressure, a 15 % increase in velocity was observed, which was stated to be due to the increased velocity of lubrication layer triggered by excitation of water movement and reduced friction resistance between the lubrication layer and the pipe wall. These advances might have the potential for applying in well construction to control the flow of common fluids in oil and gas wells, and thus improving the process while reducing the operation cost.

3.4. Potential Applications

Much of the experiences from electrokinetic application in concrete industry might be implemented in well construction. Electrokinetic techniques might be helpful in improving the drilling and cementing process through controlled rheological properties of drilling and completion fluids, pumpability, and improved cement placement. Additionally, they might be effective in fluid loss reduction in thief zones, shrinkage control [88], casing corrosion mitigation, cement-casing recovery from chemical attacks, and modification of casing-cement or casing-rock interfaces [89]. Electrorheological fluids/gel [90] might have the potential to be used in cement sheath repair and, plug and abandonment operations.

More research projects need to be conducted to investigate the potential applications and feasibility of electrorheological systems and electrokinetic methods for well construction.

4. Limitations of Electrokinetic Techniques

Application of DC electric field can induce corrosion initiation and propagation in the anodic zone, which depends on the stability of the anode, the current density, and the presence of corrosive ions such as chloride [91]. Especially at high field strength, electrochemical and chemical attacks is accelerated at the electrodes and surrounding matrix [92]. Application of absorbing electrode materials, or coating electrodes with conductive, non-corrosive material could be possible techniques to protect electrodes from corrosion.

Additionally, electrolysis of water occurs at applied voltages, and gas evolution at the electrodes is inevitable. This causes bubbles to be trapped within the cement system at vicinity of electrodes [92], which results in increased porosity. In addition, hydrogen may cause hydrogen embrittlement of steel. Pulsed DC [93-95], and asymmetric AC [96, 97] are proposed as effective way to control and suppress the amount of produced hydrogen and oxygen gases due to water electrolysis.

More so, the cement slurry may contain different admixtures depending on the placement condition. These materials might affect the cement's zeta potential [29] and even reverse the sign of the zeta potential [24], which needs to be considered when applying electrokinetic methods.

In addition to the above mentioned problems, the application process of electrokinetic methods in a well configuration is not clear. Steel casing can be used as one of the electrodes; however, positive polarization has the risk of corrosion, which will impose restrictions on the parameters of applied electric filed. In the case of electrokinetic remediation, a field-scale implementation of the method to a wellbore was proposed by Wakeel et al. (2019), see Figure 9. The steel pipe was proposed to be perforated at the top and bottom of the repair region. These perforations will be used to insert metallic pipes to carry charge and particle solution in and out of the repair section. The nanoparticles will be transported into the cement paste by the inflow and the damaging ions out of it by the outflow, which are driven by the applied electric field [85].

Recent technological advances in drilling and well construction might be helpful in development of technologies for applying electrokinetic methods in well construction. This needs contributions from both industry and academia.

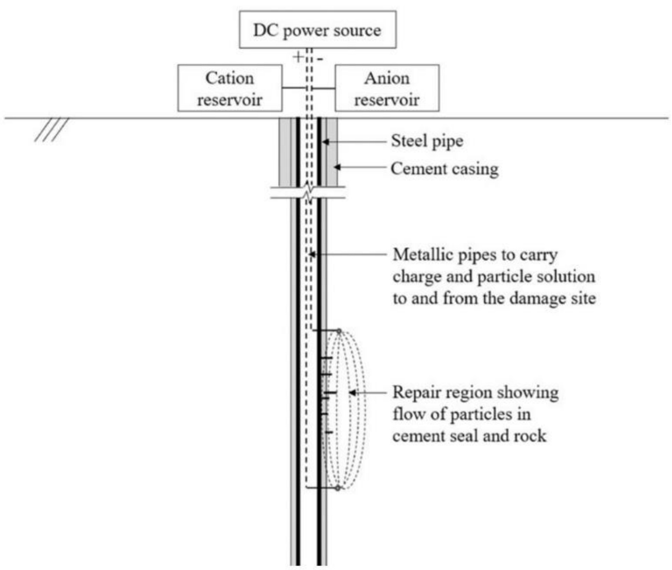

Figure 9: Proposed method applied to a wellbore [85].

5. Conclusion

Electrokinetic techniques have been applied in many disciplines enabling manipulation of materials properties. These techniques are used in the concrete industry, primarily for mitigation of reinforcement corrosion, but also to modify the microstructure of cement-based systems and thus to improve their long-term performance. Electrokinetic-based methods are proposed used for concrete demolding, curing, and treatment of damaged concrete structures. Electrokinetic treatment are used for corrosion mitigation and suggested used for refinement of microstructure/upgrading durability, crack healing, recovery from chemical attacks, and reinforcement-concrete bonding enhancement.

Feasibility of electrokinetic nanoparticle treatment has been studied for oil well cement systems. Electrokinetic methods seem promising in providing active control of system's properties in complex well condition. These advances might have the potential to be implemented in oil well construction to build a durable cement sheath for the life of the well. However, introduction of electro-techniques to well construction is in its preliminary phase and more research needs to be conducted to study their potential applications and limitations.

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