Evaluation of Self-Consolidating Concrete Robustness by Measuring Electrical Conductivity of Plastic Concrete

Payam Vosoughi[1], Mahmoud Motahari Karein[2]

[1] Ph.D. Candidate, National Concrete Pavement Technology Center, Institute for Transportation, Iowa State University of Science and Technology

[2] Ph.D. Candidate, Department of Civil and Environmental Engineering and Construction, University of Nevada at Las Vegas, Nevada, USA

Abstract:

This paper is aimed to review robustness of Self-Consolidating Concrete (SCC) in term of resistance against static segregation and bleeding. SCC is a highly fluid and non-segregating concrete able to spread through even dense reinforcement and homogenously fill formwork without using any external mechanical consolidation. Due to field requirements, SCC should be able to sustain its desired fresh properties over a relatively long time (about two or three hours) making it more susceptible to segregation than conventional concrete. Although there are a couple of proposed test methods to evaluate SCC robustness, multi electrodes electrical conductivity technique could be a reliable, non-destructive, inexpensive and simple test method to continuously monitor progress of hydration reactions (even indicating initial and final setting time) and stability (bleeding and both static and dynamic aggregate segregation) of plastic cement-based materials over the early-age period. In this paper, a brief review on fresh properties of SCC and static aggregate segregation has been taken place. Then, different methods for measuring concrete conductivity have been investigated. Afterwards, some studies on evaluation of stability of cement-based materials and SCC have been reviewed. Finally, based on the literature, some recommendations for future works are introduced.

Keywords: Self-Consolidation Concrete, Static Segregation, SCC Bleeding, Image Processing, Fresh Concrete Resistivity

Table of Contents

List of Figures

List of Tables

1- Introduction

ACI Committee 237 (2007) defines Self-Consolidating Concrete (SCC) as a highly fluid and non-segregating concrete which can spread through even dense reinforcement and homogenously fill formwork without using external mechanical consolidation. Indeed, the three major fresh property requirements of SCC are flowing ability, passing ability, and stability.

Concrete stability includes both segregation (static and dynamic) and bleeding resistance. Segregation is upward migration of fine aggregates and sedimentation of coarse aggregates. However, bleeding is movement a part of free water in the fresh mixture to the surface. According to its highly fluid nature and the practical requirement to sustain this fluidity at least for two or three hours, SCC is more susceptible to segregation and bleeding than conventional concrete. Concrete instability not only affects appearance and surface properties of concrete in practice, but also changes the strength, durability and even bond strength of concrete. Therefore, it is crucial to have quick, inexpensive and reliable test methods to evaluate these characteristics in both laboratory and field conditions.

The separation after placing concrete is called static segregation in which aggregate sinks in concrete at rest, while the separation during the process of transportation and placement is called dynamic segregation in which aggregate lags behind in flowing concrete. In common construction methods, the forces acting on the aggregate after placement are higher than those during placement (Bonen et al. 2007) that is why investigating static segregation is highly important. Nonetheless, it could not be concluded that each concrete has a good resistance against static segregation will have great performance in dynamic segregation as well.

Several test methods are available for evaluation of static segregation resistance, including Hardened Visual Stability Index (HVSI) (AASHTO PP58 2008), Column Segregation (ASTM C1610 2010), Rapid Penetration Test (ASTM C1712 2009), Sieve Segregation Resistance Test (EFNARC 2005), Modified Segregation Probe Test (Shen et al. 2014), Image Analysis of Hardened Cylinder (Fang and Labi 2007; Shen et al. 2005) and Electrical Conductivity of Plastic Concrete (C. Jolicoeur et al. 2000). Furthermore, there are some other proposed test methods such as V-Funnel (Japan Society of Civil Engineers 1999), L-Box (Japan Society of Civil Engineers 1999), U-Box (EFNARC 2005) and J-Ring (ASTM C1621 2014), which only evaluate some SCC rheological parameters which could be linked to both static and dynamic segregation (instead of directly measure segregation).

Measuring electrical conductivity of plastic concrete is a non-destructive, reliable, inexpensive and simple test method. Furthermore, it provides an opportunity to continuously monitor progress of cement hydration reactions by which concrete setting time could be accurately predicted. This paper is aimed to briefly investigate this test method and review what has been recently conducted in this area.

1-1- Self-Consolidation Concrete

In the mid-1980s, Okamura and his coworkers introduced a concrete with high workability to minimize effects of insufficient concrete consolidation on durability of structures in Japan (Ozawa K et al. 1989). Afterwards, the use of SCC is rapidly expanding around world because it not only provides more uniform concrete with better finished surface, but also reduces construction efforts, noise pollution and equipment demand. The fundamental rheological properties of SCC are based on low yield stress, moderate viscosity and retention of the kinetic energy of the flowable mix by reducing the size and volume fraction of coarse aggregate. These measures are necessary for imparting the requested fluidity, segregation resistance and prevention of interparticle collision and blocking (Bonen and Shah 2005).

1-2- Static aggregate Segregation

Static aggregate segregation mainly happen because of the density difference between aggregate and paste, rheological properties of the mixture (yield stress and viscosity), and aggregate properties such as volume fraction, gradation, and shape (Lin Shen et al. 2009). Figure 1 shows the effect of the aggregate size on the sedimentation velocity ratio of 12.7 mm aggregate of finer particles with the same density (Bonen and Shah 2005). These values are calculated based on Stocks' law assuming the aggregate particles do not interact with each other. This figure indicates that a 12.7mm aggregate settles down 10 times faster than a 4mm aggregate. More interestingly, this aggregate settles about 10000 times faster than 0.15mm aggregate. This could demonstrate one of the most important reasons of static segregation and limiting the maximum aggregate size on SCC.

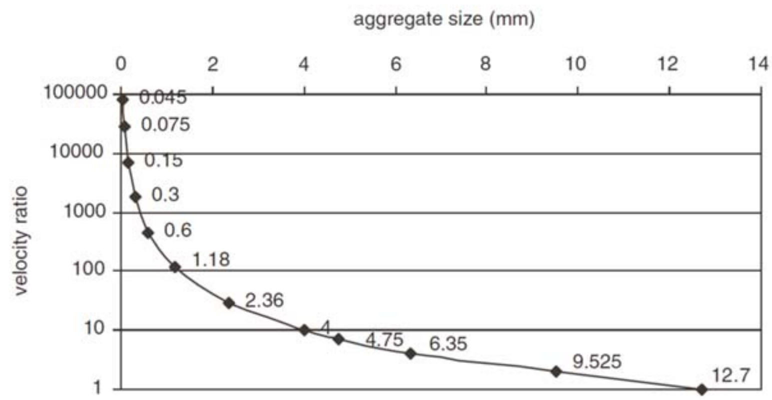


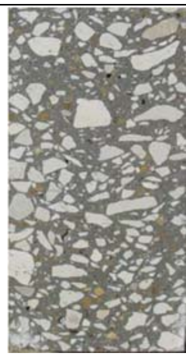
Figure 1- Sedimentation velocity ratio of 12.7 mm aggregate over finer particles with equal density (Bonen and Shah 2005)

Segregation resistance in SCC is normally achieved by reducing free water content, adding finely powdered materials such as limestone dust and slag as density modifiers or silica fume as viscosity modifier, reducing maximum aggregate size, increasing fine/total aggregate ratio (Bonen et al. 2007; Khayat et al. 2004; Lin Shen et al. 2014). Besides, a viscosity-modifying admixture (VMA), which are usually water-soluble, high molecular weight polymers such as derivatives of starch, cellulose and gums, could be used to control segregation by increasing the capacity to retain free water and increasing the viscosity of the suspended liquid phase (C. Jolicoeur et al. 2000; Kamal Henri and Zubeir 1997; Sakata et al. 1996; Siwar Naji and Kamal 2011).

Keske et al. (2013) believe that the most common stability test method for SCC is Visual Stability Index (VSI). However, this standard test method is relatively subjective and rely on experience of the operator. Also, it is recommended that some other test methods such as column segregation test, in combination with bleed test (ASTM C232) can provide a good indication of concrete static stability performance. Nonetheless, these test methods are time-consuming and to some extent difficult to repeatedly conduct in field condition.

Taking a core specimen from hardened concrete and carrying out Hardened Visual Stability Index (HVSI) test is one of the most effective test methods to assess what has finally happened inside concrete (AASHTO PP58 2008). Table 1 demonstrates four diverse concrete specimens with different stability and relevant HVSI. Nevertheless, this test method faces several limitations such as lack of expert HVSI raters, errors in human judgment, subjectivity of the ratings, and tediousness. To encounter these problems Fang and Labi (2007) introduced a new test procedure using image processing technology which could solve problems related to humane judgement. However, taking core, making ready the test specimen and conducting test is still expensive, time-consuming and required some special apparatus.

Table 1- HVSI for different hardened concrete specimen (Fang and Labi 2007)

HVSI	0 (Stable)	1 (Stable)	2 (Unstable)	3 (Unstable)
Image				
Description	No mortar layer at the top of the cut plane and no variance in size and percent area of coarse aggregate distribution from top to bottom.	No mortar layer at the top of the cut plane but slight variance in size and percent area of coarse aggregate distribution from top to bottom.	Slight mortar layer, less than 1 in. tall, at the top of the cut plane and distinct variance in size and percent area of coarse aggregate distribution from top to bottom.	Clearly segregated as evidenced by a mortar layer greater than 1 in. tall or considerable variance in size and percent area of coarse aggregate distribution from top to bottom.

2- Concrete Electrical Conductivity

Electrical conductivity has been used to study early-age properties and monitor hydration of cement-based materials since 1930s (Dorsch 1933). This test method is not only basically non-destructive, inexpensive and simple, but also appropriate to directly and continuously monitor chemical hydration reactions happening inside concrete instead of indirectly anticipate hydration progress by measuring other properties such as penetration resistance or wave propagation.

Response of any material to applied electrical impulse could be measured in terms of resistance and capacitance. Resistance could be expressed by apparent conductivity (σ) and capacitance is demonstrated by apparent dielectric constant (ε), both are frequency dependent. Figure 2 illustrates electrical dispersion of a cement paste (W/C = 0.35) over time. As it is proved, ε is decreased and σ is increased by increasing frequency; therefore, current with high frequency (at least more than 1 KHz) should be used to measured (fresh or hardened) concrete conductivity for minimizing the error because of dielectric properties of concrete (MacDonald and Northwood 1999; Taylor and Arulanandan 1974).

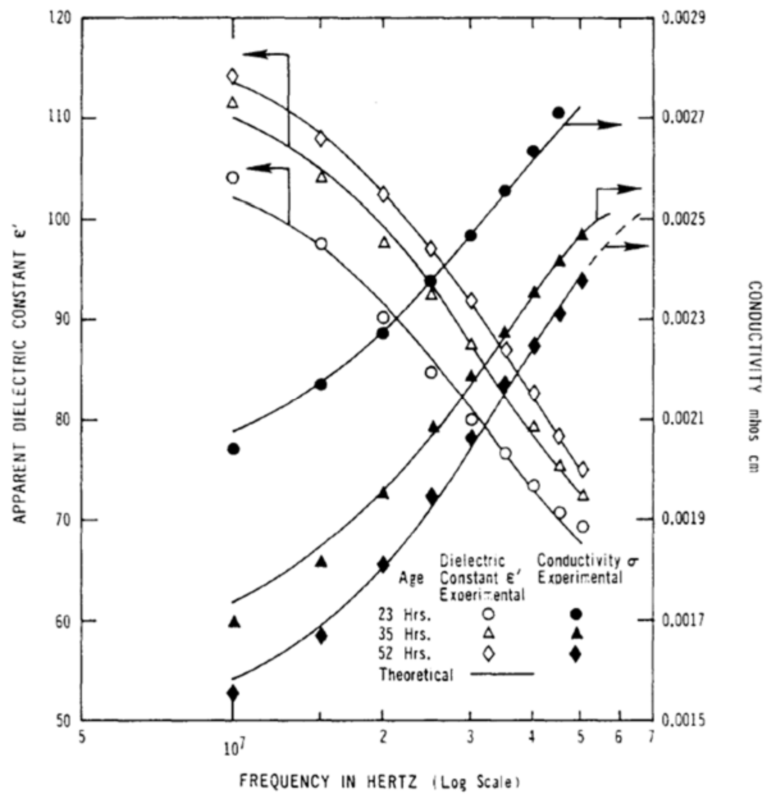


Figure 2- Dielectric Dispersion of Cement Paste (Taylor and Arulanandan 1974)

The exact value of electrical conductivity of plastic or hardened concrete is a very complex function of various parameters, including the volume fraction of the cement paste and aggregate, pore-size distribution, ionic composition of the liquid phase (mostly dependent on cement and SCM type), presence of chemical admixtures, connectivity of pore network and so on (Mesbah et al. 2011). For instance, it is worth to note that equivalent conductivity of aqueous OH^{-} at infinite concentration at 25°C is about 2.5 times more than K^+ which is the second conductive aqueous ion in cement paste (Shi 2004). Therefore, adding SCMs consuming $Ca(OH)_2$ leads to an significant increase in concrete resistivity.

Figure 3 is illustrating the variation of concrete resistivity over W/C ratio which could be increased by adding more free water or upward migration of bleeding water. Furthermore, Figure 4 demonstrates increase in concrete resistivity due to increment of aggregate fraction according to mixture design or aggregate settling. Resistivity of aggregate is much higher than that of cement-based materials; for instance, resistivity of Marble is measured about $290\ K\Omega.cm$ (Monfore 1968).

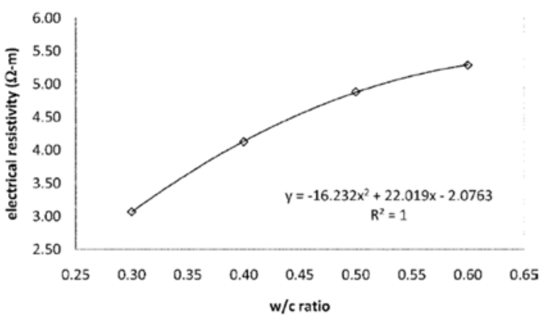


Figure 3- Relationship between electrical resistivity and W/C of fresh concrete (Mancio et al. 2010)

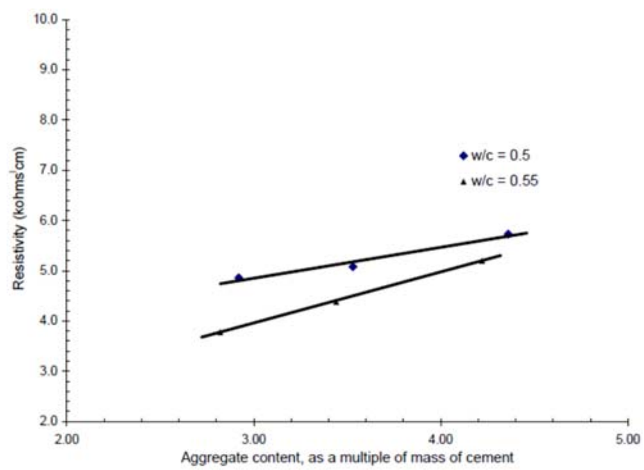


Figure 4- Aggregate content VS. concrete resistivity (Whiting and Nagi 2003)

Concrete electrical conductivity could be measured through three different methods. The first one is Direct Current (DC) method including some significant errors due to the contact resistance (R_c) and polarization effect although there are some ways to decrease the magnitude of these errors. The second one is Alternative Current (AC) which should be defined by all voltage (V), current (A) and Frequency (Hz). Gowers and Millard (1999) demonstrated that the possible error due to contact resistance is significantly less important in impedance method in comparison with DC method. Besides, the error related to polarization effect could be eliminated by using a high-frequency current (more than 1 KHz). The last method is non-contacting electrode presented in Figure 5. This method is introduced by Li et al. (2003) for measuring conductivity of plastic concrete and able to remove most important errors.

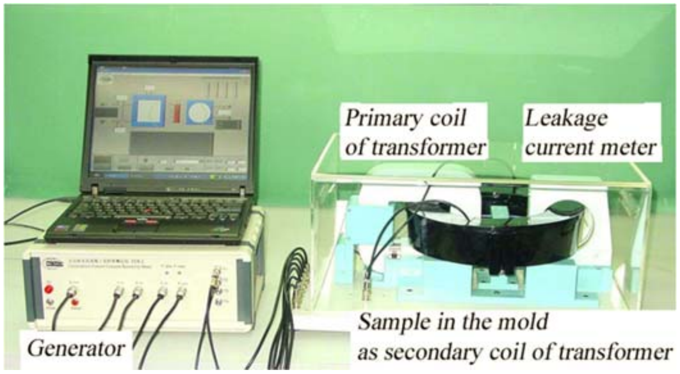


Figure 5- Setup of non-contact electrical resistivity measurement (Zuo and Wei 2013)

2-1- Variation in Plastic Concrete Conductivity

Right after mixing cement materials and water, chemical ions (such as K^+, Na^+, Ca^{2+}, OH^-, SO_4^{2-}) start to dissolve into water which significantly decreases the initial resistivity to ρ_m demonstrated on Figure 6–a (dissolving period). Thereafter, electrical resistivity gradually increase due to hydration reaction progress which not only decreases ions concentration, but also produces a non-conductive tortuous structure (setting period). Then, the rate of cement hydration is suddenly increased (hardening period) leading to a turning point in the resistivity curve representing ρ_t illustrated on Figure 6-b. Using occurrence time of these two important points, initial and final setting time of the given concrete could be defined (Li et al. 2007).

In addition, Figure 7 illustrates rate of electrical resistivity development over time. Four main periods could be identified in this diagram related to progress of cement hydration reaction: (I) dissolution and precipitation period, (II) setting period, (III) acceleration period and (IV) deceleration period.

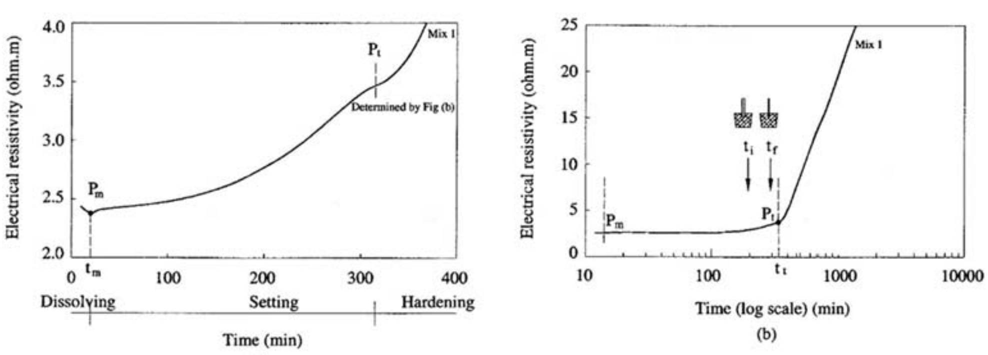


Figure 6- Increasing concrete resistivity over the very early-age (Li et al. 2007)

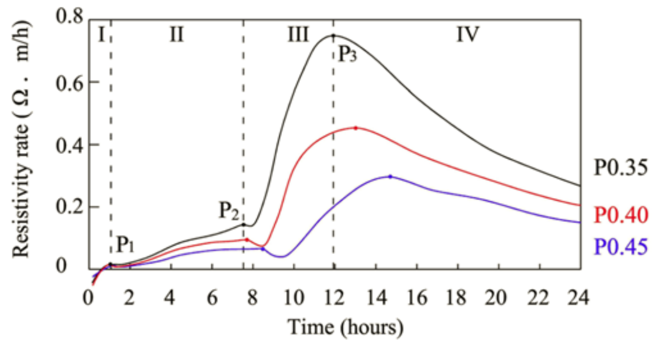


Figure 7- Rate of electrical resistivity development with time (Zuo and Wei 2013)

3- Evaluation of Stability of Plastic SCC by Measuring Concrete Conductivity

Schematic of multi electrode probe and test specimen is demonstrated on Figure 8. As it is illustrated, there are four electrode pairs along a 350 mm test column specimen; one at the top and bottom parts and two pairs on the middle of the specimen with the same distance. Right after mixing cement-based materials with water the test specimen should be filled and conductivity measurement should be started. According to measured values on different electrode pairs, the variation of conductivity over the elapsed time could be drawn and following indexes according to Table 2 could be calculated.

Figure 9 demonstrates conductivity variation of different electrode pairs along the height of an unstable concrete specimen. It shows a phase separation; due to bleeding and water upward migration local W/C ratio of the top part is increased leading to sharply increase in conductivity. Also, aggregate segregation cause an increase in local aggregate fraction in the bottom part the specimen leading to significantly decrease in conductivity. Nonetheless, variation of conductivity of a stable concrete over elapsed time is demonstrated on Figure 10.

As it is previously described, segregation index could be defined by image analysis. Figure 11 illustrates the strong correlation between what has identified by these two test methods. In addition, Figure 12 clarifies remarkable correlation between homogeneity index determined by conductivity method and segregation index calculated by image analysis. As it is exemplified, based on the homogeneity index concretes could be divided into three different categories; high, medium and low stability.

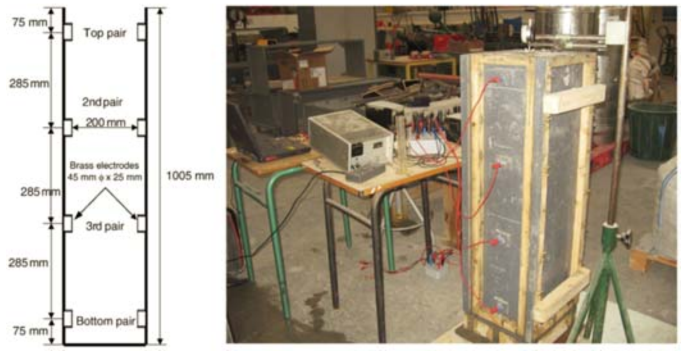


Figure 8- Schematic of multi-electrode probe and test specimen (Mesbah et al. 2011)

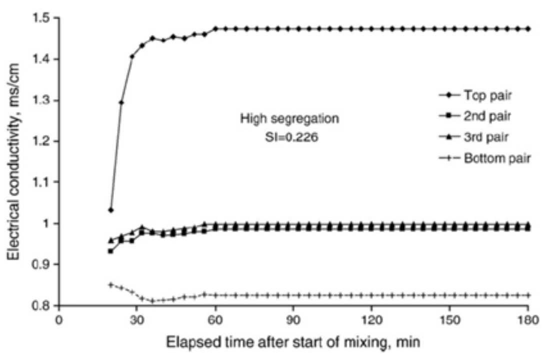


Figure 9- Variation of electrical conductivity of an unstable concrete mixture (Mesbah et al. 2011)

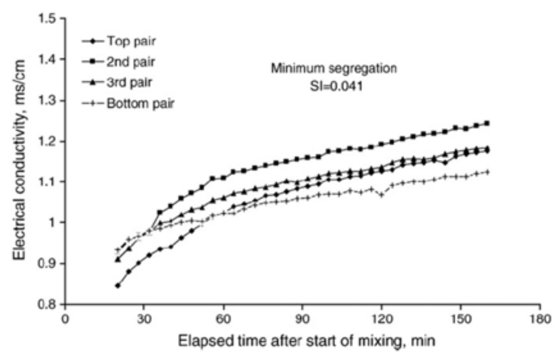
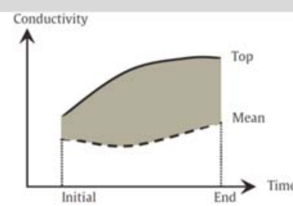
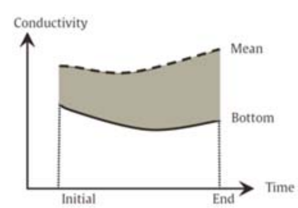
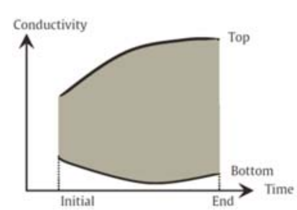


Figure 10- Variation of electrical conductivity of a stable concrete mixture (Mesbah et al. 2011)

Table 2- Definitions of stability indexes (Mesbah et al. 2011)

Index	Formula	Schematic sketch
Bleeding index	$BI = \frac{\text{Cumulative area top pair to mean}}{T_{End} - T_{initial}}$	
Segregation index	$SI = \frac{\text{Cumulative area mean to bottom pair}}{T_{End} - T_{initial}}$	
Homogeneity index	$HI = \frac{\text{Cumulative area top to bottom pair}}{T_{End} - T_{initial}}$	

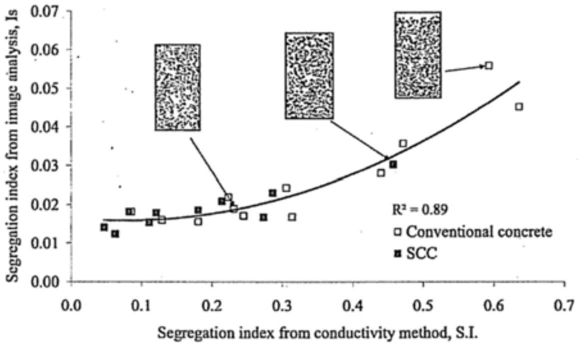


Figure 11- Correlation of segregation indexes determined by image analysis and electrical conductivity (Khayat et al. 2007)

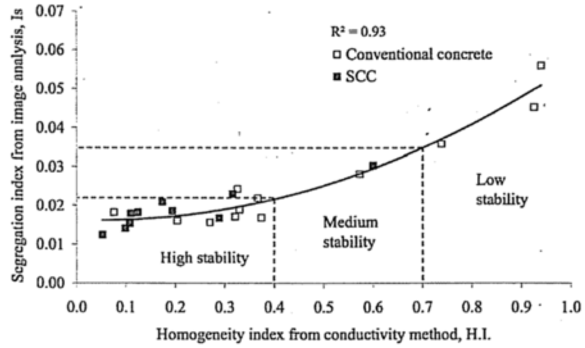


Figure 12- Relationship between segregation index determined by image analysis and homogeneity index calculated using electrical conductivity (Khayat et al. 2007)

4- Conclusion and future research

As it is explained, measuring electrical conductivity of plastic concrete is a non-destructive, reliable, inexpensive, simple and continuous test method through which not only segregation and bleeding (both internal and external one) resistance of SCC could be determined, but also progress of hydration reactions and setting time could be identified simultaneously.

It seems that more studies are required to define the minimum dimensions of the test specimen, distance between electrodes etc. according to maximum aggregate size. Besides, it would be beneficial (especially in filed condition) to propose a new test setup through which both stability and setting time are tested. In addition, it is possible to predict W/C ratio of a given fresh concrete using conductivity. Therefore, it might be possible to predict even long-term properties of hardened concrete using this test method.

5- Acknowledgement

Conducting this literature review and presenting the pertinent term paper would not be possible without efforts of the researchers whose results are used and referred in the following section. Therefore, the author wants to deeply appreciate their generosity to share their information.

6- Reference

AASHTO PP58 (2008). "Static segregation of hardened self-consolidating concrete cylinders." American Association of State Highway and Transportation Officials, Washington, DC.

ACI Committee 237 (2007). "Self-Consolidating Concrete." American Concrete Institute, Farminfton Hills, MI.

ASTM C232 (2014). "Standard Test Method for Bleeding of Concrete." American Society for Testing and Materials, West Conshohocken, PA.

ASTM C1610 (2010). "Standard Test Method for static segregation of selfconsolidating concrete using column technique." American Society for Testing and Materials, West Conshohocken, PA.

ASTM C1621 (2014). "Standard Test Method for Passing Ability of Self-Consolidating Concrete by J-Ring." American Society for Testing and Materials, West Conshohocken, PA.

ASTM C1712 (2009). "Standard Test Method for rapid assessment of static segregation resistance of self-consolidating concrete using penetration test." American Society for Testing and Materials, West Conshohocken, PA.

Bonen, D., Deshpande, Y., Olek, J., Shen, L., Struble, L., Lange, D., Khayat, K., De Schutter, G., and Boel, V. "Robustness of self-consolidating concrete." *Proc., 5th International RILEM Symposium on Self-Compacting Concrete*, RILEM Publications SARL, 33-42.

Bonen, D., and Shah, S. P. (2005). "Fresh and hardened properties of self-consolidating concrete." *Progress in Structural Engineering and Materials*, 7(1), 14-26.

C. Jolicoeur, K. H. Khayat, T. Pavate, and Page, M. (2000). "Evaluation of Effect of Chemical Admixture and Supplementary Cementitious Materials on Stability of Cement-Based Materials Using In-Situ Conductivity Method." *ACI Special Publication*, 195.

Dorsch, K. (1933). "The hardening and corrosion of cement-IV." *Cement and Cement Manufacture*, 6(4), 131-142.

EFNARC (2005). "The European guidelines for self-compacting concrete, experts for specialized construction and concrete systems." Self-Consolidation Concrete European Project Group, ed.Farnham, UK.

Fang, C., and Labi, S. (2007). "Evaluating the Static Segregation Resistance of Hardened Self-Consolidating Concrete using Image Processing Technology." *Transportation Research Record*, 2020, 1-9.

Gowers, K., and Millard, S. (1999). "Measurement of concrete resistivity for assessment of corrosion severity of steel using Wenner technique." *ACI Materials Journal*, 96(5).

Japan Society of Civil Engineers (1999). "Recommendation for self-consolidating concrete." Omoto T., and O. K., eds., JSCE concrete engineering.

Kamal Henri, K., and Zubeir, G. (1997). "Use of Viscosity-Modifying Admixture to Enhance Stability of Fluid Concrete." *ACI Materials Journal*, 94(4).

Keske, S. D., Schindler, A. K., and Barnes, R. W. (2013). "Assessment of Stability Test Methods for Self-Consolidating Concrete." *Aci Materials Journal*, 110(4), 385-393.

Khayat, K. H., Assaad, J., and Daczko, J. (2004). "Comparison of field-oriented test methods to assess dynamic stability of self-consolidating concrete." *ACI Materials Journal*, 101(2), 168-176.

Khayat, K. H., Vanhove, Y., Pavate, T. V., and Jolicoeur, C. (2007). "Multi-electrode conductivity method to evaluate static stability of flowable and self-consolidating concrete." *ACI materials journal*, 104(4).

Li, Z., Wei, X., and Li, W. (2003). "Preliminary interpretation of Portland cement hydration process using resistivity measurements." *ACI Materials Journal*, 100(3).

Li, Z., Xiao, L., and Wei, X. (2007). "Determination of Concrete Setting Time Using Electrical Resistivity Measurement." *Journal of Materials in Civil Engineering*, 19(5), 423-427.

Lin Shen, Hamed Bahrami Jovein, Shihui Shen, and Li, M. (2014). "Effects of Aggregate Properties and Concrete Rheology on Stability Robustness of Self-Consolidating Concrete." *Journal of Materials in Civil Engineering*, 0(0), 04014159.

Lin Shen, Struble, L., and David, L. (2009). "Modeling Static Segregation of Self-Consolidating Concrete." *ACI Materials Journal*, 106(4).

MacDonald, K., and Northwood, D. (1999). "Rapid Estimation of Water-Cementitious Ratio and Chloride Ion Diffusivity in Hardened and Plastic Concrete by Resistivity Measurement." *ACI Special Publication*, 191.

Mancio, M., Moore, J. R., Brooks, Z., Monteiro, P. J., and Glaser, S. D. (2010). "Instantaneous Determination of Water-Cement Ratio of Fresh Concrete." *ACI Materials Journal*, 107(6).

Mesbah, H. A., Yahia, A., and Khayat, K. H. (2011). "Electrical conductivity method to assess static stability of self-consolidating concrete." *Cement and Concrete Research*, 41(5), 451-458.

Monfore, G. E. (1968). "The electrical resistivity of concrete." *Journal of the PCA Research and Development Laboratories*, 10(2), 35-48.

Ozawa K, Maekawa K, Kunishima M, and H, O. (1989). "Development of high performance concrete based on the durability design of concrete structures." *Second East-Asia and Pacific conference on structural engineering and construction*, Okamura H, and S. H, eds.Kochi, Japan, 445–450.

Sakata, N., Maruyama, K., and Minami, M. "Basic Properties of Viscosity Agent Welan Gum and Effects on Self-Consolidating Property of Fresh Concrete." *Proc., Proceedings-Japan Society of Civil Engineers*, Dotoku Gakkai, 57-68.

Shen, L., Jovein, H. B., and Li, M. (2014). "Measuring static stability and robustness of self-consolidating concrete using modified Segregation Probe." *Construction and Building Materials*, 70(0), 210-216.

Shen, L., Struble, L., and Lange, D. "Testing static segregation of SCC." *Proc., Proceedings of the 2nd North American Conference on The Design and Use of SCC*, 729-737.

Shi, C. (2004). "Effect of mixing proportions of concrete on its electrical conductivity and the rapid chloride permeability test (ASTM C1202 or ASSHTO T277) results." *Cement and Concrete Research*, 34(3), 537-545.

Siwar Naji, S.-D. H., and Kamal, H. K. (2011). "Robustness of Self-Consolidating Concrete Incorporating Different Viscosity-Enhancing Admixtures." *ACI Materials Journal*, 108(4).

Taylor, M. A., and Arulanandan, K. (1974). "Relationships between electrical and physical properties of cement pastes." *Cement and Concrete Research*, 4(6), 881-897.

Whiting, D. A., and Nagi, M. A. (2003). "Electrical resistivity of concrete-a literature review." *R&D Serial*(2457).

Zuo, Y., and Wei, X. (2013). "Portland cement hydration by electrical resistivity method and computer simulation." *Journal of Testing and Evaluation*, 41(3), 451-457.