VARIATIONS IN UPV MEASUREMENTS DUE TO AGGREGATE SEGREGATION IN CONCRETE

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ABSTRACT

Advancements in both concrete technologies and construction methods warrant the evaluation of the adequacy of non-destructive testing and predictive equations to evaluate mechanical properties of concrete. This is of particular significance owing to the fact that, highly flowable mix designs are gaining attention for new construction, including mass concrete, and repair applications owing to its unique and desirable plastic properties which can pass between reinforcement and through constrictions in formwork but are however vulnerable to segregation. The focus of this study is to examine the effect of aggregate segregation on UPV measurements and compressive strength estimates.

INTRODUCTION

The management and challenges associated with ageing nuclear structures have been widely reported by the international nuclear community for the past two decades [1, 2, 3]. This has naturally brought the discussion related to new design and construction of nuclear facilities to the forefront [4, 5, 6, 7]. Given the high degree of sophistication of nuclear design projects, future facilities built in the 21st century will no doubt employ state of the art construction practices, utilization of advanced materials, and structural design innovations in attempt to optimize construction schedules, minimize adverse environmental impacts, and achieve longer service lives than plants of the previous generation. Advanced concrete materials to achieve improved strength, workability, and resistance to reinforcement corrosion have been implemented in large civil projects including nuclear related facilities, dams, and bridges.

Since the construction of nuclear power plants in Canada, 1970-80ies, the state of traditional concrete has advanced largely owing to usage of admixtures. Admixtures are used to achieve enhanced workability, improved mechanical properties, lower permeability, limited shrinkage, and greater durability performance. High performance concrete, self consolidating concrete, and reactive powder concretes are examples of types of concretes that have gained attention over the past 20 years, and consist of various types of admixtures, both chemical (water-reducing agent, air entraining agent, superplasticizer, viscosity modifying agent, etc.) and mineral (fly ash, ground granulated blast furnace slag, etc.). The use of self consolidating concrete is particularly advantageous for confined spaces, and structures that are heavily reinforced and prestressed as is typical in nuclear related concrete structures. Although the impact of self consolidating concrete may have some minimal benefit on the construction schedule, it has been reported that the reduction in labour costs outweigh the relatively higher cost of the concrete materials [7]. Within the nuclear industry, civil engineers, concrete researchers and material scientists are currently faced with challenges associated with: improving the efficiency of construction; improving the quality and measurement of plastic, and hardened properties of concrete; while simultaneously making economically feasible decisions. Moreover, when new material technologies are used in nuclear related applications it is imperative to investigate the material behaviour in the plastic and hardened state and non destructive approaches to assess them.

For years, ultrasonic pulse velocity (UPV) has been used extensively to assess the homogeneity of concrete [8]. Measurements can be taken in a rapid, non destructive manner with test equipment that is user friendly. Ultrasonic pulse velocity has been shown in the literature to be linked to elastic properties of concrete. Many

studies have shown the correlation between UPV and the compressive strength of high strength concrete, dry cast concrete, conventional concrete and self consolidating concrete [9, 10, 11]. Literature on nuclear structures has indicated that utilization of UPV has traditionally contributed to the quantification of capabilities for measuring thickness, mapping reinforcement, and detecting voids [12]. This investigation examines the role of UPV used as a non destructive approach to determine the impact of segregation on the compressive strength of concrete for nuclear applications. This is of particular significance owing to the fact that, highly flowable mix designs are gaining attention for new construction, including mass concrete, and repair applications owing to its unique and desirable plastic properties. Recent studies have reported the utilization of concrete with a low viscosity for heavily reinforced structures such as radioactive waste disposal of super containers, base slab, and also repair applications [13].

Concrete technologies such as high performance concrete, and self consolidating concrete, commonly use chemical admixtures in order to control water content, entrained air content, viscosity, slump and plastic properties such as filling ability, passing ability and segregation resistance. Although highly flowable concretes are known to exhibit desirable plastic properties, they are vulnerable to segregation. Beyond the need for a cohesively designed mixture, potential causes of segregation may be attributed to the compatibility of chemical admixtures including superplasticizers, air entertainers, and viscosity modifying agents, and/or constructability related aspects such as reinforcing steel configuration, or pumping pressures. Segregation may occur during the mixing and placement of the material, or after the concrete has been placed, and is referred to as dynamic stability and static stability, respectively. The differential settlement of the constituents typically yields settlement of the coarse aggregate leaving the top surface rich is paste, and possibly air and free water.

Recent studies have indicated that the effect of coarse aggregate segregation on the compressive strength can be masked if the quality of the materials (ie. aggregate, cementing material, supplementary cementing materials etc.) are good, and the mix proportions are within limits suggested by codes and/or guidelines [14, 15]. This finding was reported when concrete compressive strengths were measured on cylinders 100 mm in diameter x 200 mm high which exhibited varying degrees of segregation resistance based on the visual stability index (VSI) and the column segregation method [15]. However, it should be noted that the column segregation measurement in accordance with ASTM C1610 [16], is based on two aggregate measures, one measurement taken from the bottom of the cylinder, and another measurement taken from the top of the cylinder. Based on this approach, this study examines the potential for UPV measurements to reflect different levels of segregation when the top and bottom of the cylinder are considered separately. So, measurements were taken on specimens 100 mm in diameter x 100 mm high cut from 100 mm diameter x 300 mm high cylinders. In theory, the path length which is the distance travelled by the wave from the transducer to the receiver should not affect the propagation time, and in turn the UPV measurement. However, it is well documented, that given the heterogeneity of concrete materials, minimum specified path lengths are suggested corresponding to coarse aggregate size. In general, the larger the coarse aggregate size, the larger the minimum distance. For example, for path lengths of 100 mm and 150 mm, a minimum aggregate size of 30 mm and 40 mm, respectively is suggested [8].

This paper is focused on an experimental study which evaluates the potential for segregation to be reflected by a non destructive approach and so investigates using UPV. Mixtures which exhibited ‘low’, ‘moderate’, and ‘high’ levels of segregation based on the VSI [17] and column method [16] were investigated. The significance of this study relates to the importance of non destructively assessing the static elastic modulus which is an important concrete property used for: designing and analyzing the strength and serviceability of concrete structures; its direct effect on creep calculations used in prestressing design; and its use to estimate strength for critical construction activities. Direct evaluation of the static elastic modulus in accordance with ASTM C469 [18] is often facilitated with the use of empirical prediction equations. Although there are many expressions which relate the elastic modulus to compressive strength, many factors can affect the concrete’s stress-strain behaviour. As a result, it is necessary to examine which empirical equations that relates the static elastic modulus to compressive strength is most suitable [19].

This forms the motivation of this study, which is very specifically to investigate the potential ability of UPV measurements as a non destructive tool to identify coarse aggregate segregation in low viscosity concrete mix designs. Ultrasonic pulse velocity has been used for decades, and continues to be a proven as an appropriate method given the current advancements with concrete technology, particularly the attractive highly flowable concrete mixtures for heavily reinforced concrete nuclear related structures.

EXPERIMENTAL PROGRAM

Materials and Methods

All of the mixtures consist of 75% General Use (type GU) cement with 25% ground granulated blast furnace slag (GGBFS) as cement replacement, have a w/b ratio of 0.4, and the sand and stone proportions are 60:40. The maximum nominal aggregate size is 13 mm. The concrete includes chemical admixtures including a superplasticizer, air entraining agent and a viscosity modifying agent. The mixtures all exhibited a slump flow between 600-700 mm. Segregation resistance was evaluated in accordance with the column method ASTM C1610 [16] and the VSI in accordance with ASTM C1611 [17]. The hardened density and compressive strength was measured in accordance with ASTM C138 [20] and ASTM C39 [21], respectively. The compressive strength tests were conducted on concrete cylinders with 100 mm diameter and 200 mm height. UPV measurements are reported for three repeats per cylinder for six cylinders and were conducted in accordance with ASTM C597 [22]. Ultrasonic pulse velocity measurements were taken on 100 mm diameter x 100 mm high specimens cut from a cylinder 300 mm high.

RESULTS AND ANALYSIS

Elastic Properties of Concrete

Ultrasonic pulse velocity is a non destructive test method used to evaluate changes in elastic modulus without damaging the concrete element or structure and is evaluated in accordance with ASTM C597 [22]. The *UPV* (m/s) measurement is directly related to the dynamic elastic modulus (E_d) (Pa), density (ρ) (kg/m^3), and the dynamic Poisson's ratio (υ) as shown in Eq. (1).

$$UPV = \sqrt{\frac{E_d(1-\upsilon)}{\rho(1+\upsilon)(1-2\upsilon)}} \tag{1}$$

This study assumes a dynamic Poisson's ratio equal to 0.2 [23]. Based on the assumed Poisson's ratio of 0.2, the measured density and UPV, Eq.(1) is used to compute the dynamic elastic modulus. To assess the correlation between the dynamic and static elastic modulus, the literature shows the linear increase in both static and dynamic elastic modulus with age. As expected, the dynamic elastic modulus is larger than the static elastic modulus due to the non-linear stress-strain behaviour of concrete [14, 24]. Panesar and Shindman [14] report the mean dynamic-to-static elastic modulus ratio is 1.70, 1.54, 1.50, 1.34, and 1.32 at days 1, 3, 7, 28 and 56, respectively. Mesbah et al. [24] report ratios of approximately 1.8, 1.5. 1.4 and 1.3 at days, 1, 3, 7, and 28. In this study, the concrete examined is one year old, and so an Ed/Es ratio of 1.3 is used in order to estimate the static elastic modulus.

Since the compressive strength of the top and bottom specimens are 100 mm diameter x 100 mm high, they can not be experimentally tested in accordance with ASTM C39 [21] and so empirical equations a function of UPV and the compressive strength are used. Three commonly used prediction equations: ACI363 [25] (Eq.(2)), ACI318 [26]/AASHTO [27] (Eq.(3)), and EuroCode2 [28] (Eq.(4)) are shown. For all equations, f'_c is the compressive strength (MPa), w_c is the unit weight of concrete (kg/m^3), and E_s is the static elastic modulus (MPa).

$$E_s = 6900 + 3300\sqrt{f_c'} \qquad \text{for 21 MPa} < f_c' < 83 \text{ MPa} \tag{2}$$

$$E_s = 0.043 w_c^{1.5}\sqrt{f_c'} \qquad \text{for 1500 kg/m}^3 < w_c < 2400 \text{ kg/m}^3 \tag{3}$$

$$E_s = 21500\left(\frac{f_c'}{10}\right)^{2/3} \tag{4}$$

Khayat and Mitchell [29] and Panesar and Shindman [14] recommend that ACI318/AASHTO Eq.(2) be used for concrete mixtures which exhibit self consolidating properties. Figure 1 shows the measured compressive strength in accordance with ASTM C39 plotted against the predicted compressive strength based on Eq. (2), (3) and (4). Figure 1 shows that the ACI363 Eq.(2) markedly overestimates the actual compressive strength, whereas the EuroCode2 Eq.(3) markedly underestimates the compressive strength. The measured compressive strengths were taken at 56 days as reported in [14]. The ACI 318/AASHTO Eq.(3) provides the closest estimate of the one year old compressive strength. Based on the close estimates of the ACI 318/AASHTO equation, it will also be used to estimate the impact of segregation on compressive strength, based on UPV measurements taken on the top and bottom section of a cylinder.

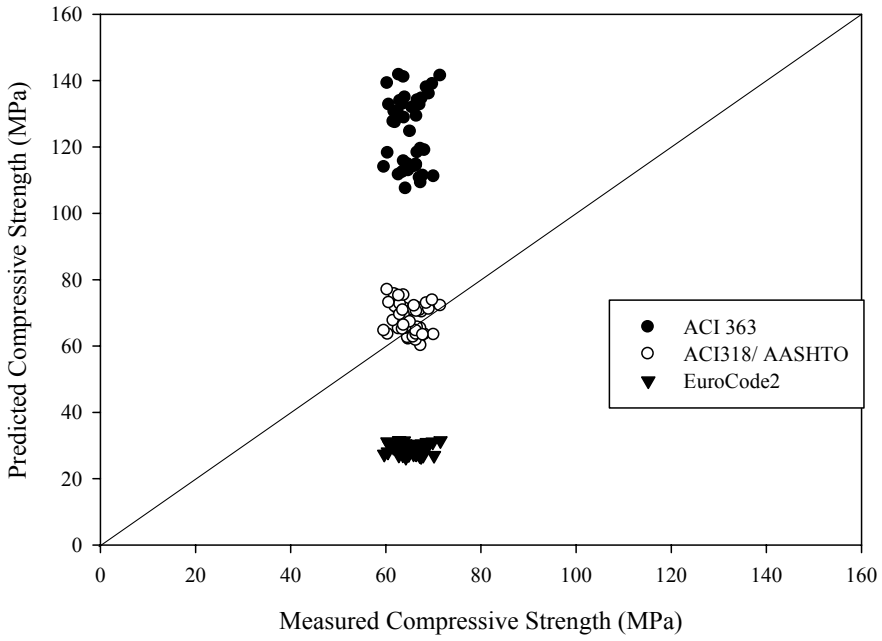

Figure 1: Measured vs predicted compressive strength at 56 days

Segregation Categories

In this study, the segregation categories, low (L), moderate (M) and high (H), are based on the currently proposed acceptance limits for VSI and the column method. The Canadian Standards Associate (CSA) 23.1 [30] states the acceptance limit for the column segregation test, and a VSI to be 10% and 1.5, respectively.

Low:	VSI $\leq$ 1.5	and	Column Segregation $\leq$ 10%
Moderate:	VSI $\geq$ 2.0	and	Column Segregation $\leq$ 10%
High:	VSI $\geq$ 2.0	and/or	Column Segregation $\geq$ 10%

Table 1 summarizes the range in VSI, and column segregation for the mixtures categorized as low, moderate and high segregation, LS, MS, and HS, respectively.

Table 1: Categorization segregation based on VSI and the column technique

Categorization Level of Segregation	Segregation Measurement	
	Visual Stability Index (VSI)	Column Segregation Technique (%)
Low	1.0 - 1.5	1.9 - 6.8
Moderate	2	7.7 - 9.6
High	2.0 - 3.0	9.9 - 11.5

Impact of Segregation on Compressive Strength Estimates – Variation with cylinder height

To investigate the effects of segregation on the non destructive estimate of compressive strength, the variation of UPV with depth was assessed. Cylinders 100 mm in diameter and 300 mm in height were cut in order to examine the UPV of the bottom portion (100 mm diameter x 100 mm high) of the cylinder in comparison to the top portion of the cylinder. This was done to examine if the differential settlement of the constituents impact the concrete's mechanical properties when local regions of the cylinder are examined separately. Similar to previously discussed, the UPV measurements in accordance with ASTM C 597 were taken on the top and bottom portions of the cylinder. The UPV measurements were used to: compute the dynamic elastic modulus based on Eq.(1) assuming a Poisson's ratio of 0.2; estimate the static elastic modulus based on an Ed/Es ratio of 1.3, and; estimate the compressive strength based on the ACI 318/AASHTO Eq.(3).

Table 2 summarizes the mean, standard deviation (st.dev.), and coefficient of variation (COV) of the compressive strength estimates for the bottom and top portion of the cylinders for concrete categorized by the severity of segregation. The results reveal that in all cases, the mean strength of the top portion of the cylinder is less than the bottom surface of the cylinder as shown in Fig. 2. An analysis was conducted to evaluate if the difference between the mean compressive strength (top vs. bottom specimen) are statistically significantly different. A student's t-test at a 95% confidence level was conducted. The results revealed that for concrete with high segregation (HS1, HS2), the difference between the top and bottom mean compressive strength is statistically significantly different. The COV of the highly segregated concrete is at least almost twice as large for the top specimen as compared to the bottom specimen.

The mean compressive strength estimates for moderate segregation MS1, MS2, indicated that the difference between the top and bottom specimens are statistically insignificant. The insignificant difference between the properties of the top and bottom of the cylinder is also supported by the COV data which shows that the COV is greater for the bottom surface compared to the top surface which is the opposite compared to the low and highly segregated concrete.

It was expected that there would be no statistically significant difference between the compressive strength of the top and bottom specimens of the low segregation concrete, LS1 and LS2. However, the results shown in Table 2, revealed that this was true for LS2 but not for LS1. The mean strength for the bottom specimens are close, 67.0 and 65.1 MPa, for LS2 and LS1 respectively, and the means for the top surface are similar, 60.3 and 59.3 MPa for LS1 and LS2, respectively. The results may partly be explained by the smaller COVs for the top and bottom specimens of LS1 in comparison to LS2 as shown in Table 2.

CONCLUDING REMARKS

Ultrasonic pulse velocity has traditionally been reported to play a significant role to evaluate the ageing nuclear related to the detection of voids, element thickness, identification of reinforcement locations. This study examined UPV as an effective non destructive approach to detect segregation resistance of highly flowable mixtures. This is

of particular importance since the usage of self consolidating concrete is an option for mass concrete and heavily reinforced elements related to nuclear applications.

A key outcome from this study revealed that utilization of UPV measurements to estimate changes in compressive strength along the height of a sample is influenced by aggregate segregation. This is a significant finding, because, the effect of segregation is not apparent when the mechanical properties (elastic modulus, compressive strength) of standard 100 mm diameter x 200 mm high cylinders are evaluated.

Key findings from this study reveal that:

- Concrete that does not exceed one or both CSA limits for VSI and column segregation, in general, do not yield statistically significant differences in estimated compressive strengths of the top vs. the bottom of the cylinder based on UPV measurements.
- Based on the VSI, and column segregation test criteria, moderately segregated mixtures do not reveal any statistically significant difference between the strength estimate of the top and bottom measurements.
- Concrete that exceeds the currently proposed CSA acceptance limit for both VSI and the column test is categorized as highly segregated. This concrete does exhibit statistically significantly different compressive strength estimates of the top of the cylinder in comparison to the bottom of the cylinder which are based on UPV measurements. In addition, the COV of the compressive strength estimate is approximately at least twice as large for the top surface measurements as compared to the bottom surface.
- Highly segregated concrete exhibited a 10 to 12 MPa reduction in estimated compressive strength of the top specimen in comparison to the bottom specimens based on UPV measurements.

Table 2: Impact of segregation on compressive strength estimates

Level of Segregation	Statistical Description	Estimated f'c ACI 318/ AASHTO		Statistically Significant Difference Between Means of Top & Bottom Specimens (Yes or No)
		Bottom Region of Specimen	Top Region of Specimen	
Low Segregation LS1	mean (MPa)	67.0	60.3	yes
	st. dev. (MPa)	1.7	5.4	
	COV (%)	2.5	8.9	
Low Segregation LS2	mean (MPa)	65.1	59.3	no
	st. dev. (MPa)	3.5	7.0	
	COV (%)	5.3	11.8	
Moderate Segregation MS1	mean (MPa)	64.6	69.7	no
	st. dev. (MPa)	5.1	5.0	
	COV (%)	7.9	7.2	
Moderate Segregation MS2	mean (MPa)	65.2	61.3	no
	st. dev. (MPa)	7.4	2.5	
	COV (%)	11.3	4.1	
High Segregation HS1	mean (MPa)	71.1	59.3	yes
	st. dev. (MPa)	6.2	9.8	
	COV (%)	8.7	16.6	
High Segregation HS2	mean (MPa)	64.2	54.7	yes
	st. dev. (MPa)	2.0	8.1	
	COV (%)	3.1	14.8	

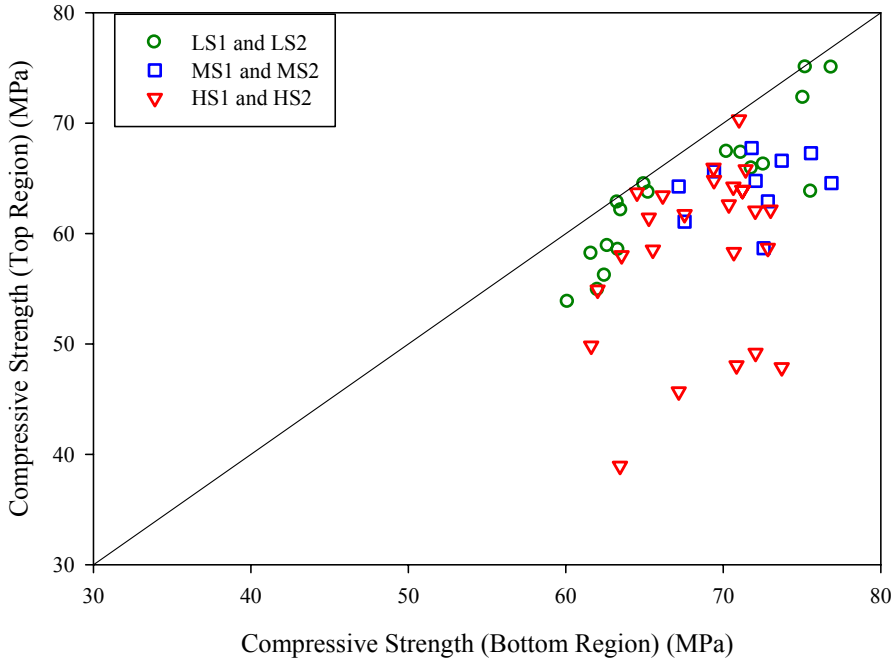

Figure 2: The influence of low (L), moderate (M) and high (H) segregation on the compressive strength of the top and bottom specimens retrieved from a concrete cylinder.

Acknowledgements

The author is grateful for the support and funding provided by the Ministry of Transportation of Ontario's Highway Infrastructure Innovation Funding Program and the National Science and Engineering Research Council for this ongoing research project at the University of Toronto. The author would like to also acknowledge Mr. B. Shindman for conducting the tests.

REFERENCES

[1] Hookham, C.J., "Structural ageing assessment methodology for concrete structures in nuclear power plants", ORNL/NRC/LTR-90-17. Contractor Report.1993.

[2] Naus, D. "Structural ageing program. Five year plan: 1989-1993", ORNL/NRC/LTR-89/15. Oak Ridge National Laboratory, Oak Ridge Tennessee. 1989.

[3] IAEA (International Atomic Energy Agency) "Ageing management for nuclear power plants- Safety guide". *IAEA Safety Standards Series* No. NS-G-2.12. IAEA, Vienna. 2009, 65p.

[4] Braverman, J.I., Hofmayer, C.H., Morante, R.J., Shteyngart, S., Bezler, P. "Assessment of age-related degradation of structures and passive components for U.S. nuclear power plants", NUREG/CR-6679, BNL-NREG-52587, Brookhaven National Laboratory, U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research Washington, DC 20555-0001. 2000, 196p.

[5] Faidy, C. (2009) "Ageing management program- A key issue for operating plants and new design", *20th International Conference on Structural Mechanics in Reactor Technology (SMiRT 20),* Espoo, Finland, Aug.2009, Division 8, paper 2595.

[6] Blahoianu, A., Gott, K., Huerta, A., Sekimura, N, and Yamamoto, A. "Ageing management, NEA News", 2009, No. 27.1. pp.16-19.

[7] Schlaseman, C. and Russell, J. "Application of advanced construction technologies to new nuclear power plants", MPR-2610 Rev.2. for U.S. Department of Energy. 2004, 132p.

[8] Malhotra, V. M. and Carino, N.J. (2004) Handbook on Nondestructive Testing of Concrete, 2nd Edition, CRC Press.

[9] Gul R, Demirboga R, Guvercin T. "Compressive strength and ultrasound pulse velocity of mineral admixtured mortars", *Indian J of Eng and Mats Sci*. 2006,Vol. 13, pp.18-24.
[10] Ulucan ZC, Turk K, Karatas M. "Effect of mineral admixtures on the correlation between ultrasonic velocity and compressive strength for self-compacting concrete", *Russian J of Non-Destruc Testing*. 2008, Vol. 44(5), pp. 367-374.
[11] Liu M. "Self compacting concrete with different levels of pulverized fuel ash", *Construc and Build Mats*. 2010 Vol. 24, pp.1245-1252.
[12] NEA/CSNI/R(98)6 "Development priorities for non-destructive examination of concrete structures in nuclear plant" 1998.p 62.
[13] Craeye, B., DeSchutter, G., Van Humbeeck, H., Van Cotthem A. "Early age behaviour of concrete supercontainers for radioactive waste disposal", *Nuc Eng and Design*. 2009, Vol. 238(12), pp.23-35.
[14] Panesar, D.K., Shindman, B. "Elastic Properties of Self Consolidating Concrete" *Construct and Build Mat*. 2011,Vol.25, pp.3334-3344.
[15] B. Shindman, D.K. Panesar, "A comparison of segregation test methods: visual stability index and column method", *Proceedings Vol. II Self-Consolidating Concrete (SCC) 2010- Design Production, and Placement of SCC 6th International RILEM Symposium on SCC*, Montreal, Quebec, Canada. Eds K. Khayat, D. Feys. 2010, p.563-571.
[16] American Society for Testing and Materials ASTM C1610 Standard Test Method for Static Segregation of Self-Consolidating Concrete Using Column Technique. ASTM Standards, West Conshohocken, Pa.. 2006.
[17] American Society for Testing and Materials. ASTM C 469-02 Standard test method for static modulus of elasticity and Poisson's ratio of concrete in compression. ASTM Standards, West Conshohocken, Pa.. 2002.
[18] American Society for Testing and Materials, ASTM C1611/C1611M-09 Standard Test Method for Slump flow of Self Consolidating Concrete 2009.
[19] Suksawang, N., Nassif, H. H., Najim, H. S. "Evaluation of mechanical properties for self-consolidating, normal and high performance concrete", Transportation Research Record: *J Transport Res Board*, 2006, Vol 1979, pp.36-45.
[20] American Society for Testing and Materials. ASTM C138/C138M - 10a Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete. ASTM Standards, Philadelphia, Pa., 2010.
[21] American Society for Testing and Materials. ASTM C39-05 Standard Test for Compressive Strength of Cylindrical Concrete Specimens. ASTM Standards, Philadelphia, Pa. 2006.
[22] American Society for Testing and Materials. ASTM C597-02 Standard Test Method for Pulse Velocity through Concrete. ASTM Standards, Easton, MD. 2006.
[23] Oluokun FA, Burdette EG, Deatherage JH. "Elastic modulus, Poisson's ratio and compressive strength relationship at early ages". *ACI Mats J*. 1991, Vol. 88 (1), pp. 3-10.
[24] Mesbah HA, Lachemi M, Aitcin P-C., "Determination of elastic properties of high-performance concrete at early ages", *ACI Mats J*. 2002, Vol. 99(1), pp. 37-41.
[25] ACI 363 ACI Committee 363R-92 State-of-the-Art Report on High Strength Concrete. American Concrete Institute, Farmington Hills, Mich. 1997.
[26] ACI 318-05 Building Code Requirements for Structural Concrete and Commentary. ACI Farmington Hills, Mich. 2005.
[27] AASHTO LRFD Bridge Design Specification for Highway Bridges. 3rd ed. AASHTO, Washington, D.C., 2002.
[28] EuroCode 2: Design of Concrete Structures. EN-1992-2, Comite European de Normalisation (CEN), Brussels, Belgium. 2005.
[29] Khayat, K.H., and Mitchell, D. NCHRP Report 628 "Self-Consolidating Concrete for Precast, Prestressed Concrete Bridge Elements", *Transport Res Board,* Washington, D.C., 2009.
[30] CSA A23.1-09. 2009. Concrete materials and methods of concrete construction. Canadian Standards Association. §8.6