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Self-compacting Concrete Study using Recycled Asphalt Pavement Incorporating Fly Ash, Slag and Superplasticizers

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***Abstract*— *This research evaluates the feasibility of using recycles asphalt pavement (RAP) and supplementary cementitious materials (SCMs) in self consolidating concrete (SCC). The fresh, mechanical and durability properties of SCC mixtures were investigated. A total of sixteen mixtures divided into four groups with different RAP proportions: 0, 15, 30, and 55% replacing the natural coarse aggregate (NCA), and different percentages of supplementary cementitious materials (SCMs) replacing cement:60% Fly ash (FA), 60% ground granulated blast furnace slag (S), and 30% FA and 30% S. Constant water to cementitious materials ratio of 0.4 was maintained in all mixtures. The compressive strengths at 3, 14 and 28 days and split tensile strength at 28 days were tested. The durability characteristics including the unrestrained shrinkage strain and rapid chloride permeability (RCPT) tests were conducted. The results show that while the use of RAP reduces both the compressive and tensile strengths of SCC mixtures, it increases the resistance to chloride permeability.*

***Keywords*— Self compacting concrete; Recycled asphalt pavement; fly ash; slag; supplementary cementitious materials, natural coarse aggregate.**

I. INTRODUCTION

Self-consolidating concrete is one type of high performance concrete that has high flowability and moderate viscosity.The main advantage of self-consolidating concrete over conventional concrete is that it can consolidate under its own weight without the need for mechanical vibration and without separation form its other components ((Ozawa et al. 1989; Yurugi 1998, Petersson 1998; Khayat et al. 2001; Lachemi et al., 2003; Khatib, 2008; Hossain et al., 2010, Ibrahim 2014).

The scarcity and high cost of natural coarse aggregate has prompted engineers to seek a cost effective solution for its use. Recycled materials such as RAP provide an alternative to natural coarse aggregate. Only 80% of the 100 million tons of hot mix asphalts (HMA) reclaimed each year are used as recycled asphalt pavement (Solanki et al., 2013). Therefore, the use of RAP as a substitute for NCA and SCMs as a replacement for Portland cement in self consolidating concrete has been studied by many researchers. Solanki and Dash (2015) conducted an extensive experimental study that included 28 concrete mixtures incorporating different RAP and class C fly ash replacement in lieu of NCA and cement. Coarse and fine RAP (Chips and screenings) were used to replace the coarse and fine aggregates in concrete. After the cylindrical specimens were cured in the curing tank, they were tested for tensile and compressive strength after 28 days. The results showed that as the percentage of RAP replacement increased, the compressive and tensile strengths decreased. Ibrahim et al. (2014) conducted an experimental study to replace NCA and the cement with RAP and SCMs with different percentages. The fresh properties including: flowability, deformability, filling capacity and resistance to segregation, and the hardened properties including, compressive and tensile strength were studied. The results indicated that the compressive and tensile strength decreased as the percentage of RAP increased. Okafor (2010) compared the physical properties of RAPused in Portland cement concrete with concretes that were prepared using NCA. It was concluded that RAP had lower specific gravity and water absorption when compared to NCA. Additionally, the strength of the specimens made with RAP primarily depended on the bond strength between the asphalt aggregate and the mortar surrounding it. Al-Orimi et al. (2009) investigated the properties of concrete incorporating RAP. The coarse aggregate was replaced by 25, 50, 75, and 100% RAP. All mixtures were tested for slump flow, compressive strength, flexural strength, modulus of elasticity, and surface absorption test. The results indicated that concrete containing RAP should be

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used in non-structural applications. Grdicet al. (2008) studied the use of different additives such as: fly ash, silica fume, hydraulic lime and a mixture of fly ash and hydraulic lime as partial replacement for cements. Several characteristics of SCC in the fresh state such as:flowability, viscosity, passing ability, and segregation resistance were assessed. The slump flow and T50 tests were used to measure the flowability and viscosity of SCC, the L-box test is used to measure the passing ability, and the V-funnel test is used to evaluate the viscosity and filling ability of the mixtures. The results indicated that adding fly ash to the mixture containing hydraulic lime enhances the filling capacity and fluidity of SCC mixtures. Additionally, using silica fume produces concrete mixtures comparable to normal concrete compacted by vibrations. Lachemiet al. (2003) evaluated the performance of SCC prepared with FA, S, and different types of viscosity modifying agents (VMAs) based on the fresh and mechanical properties as well as cost. The cement was replaced with FA by 40, 50, and 60%, and slag by 50, 60, and 70%. Water cement ratio of 0.35-0.45 was used in the mixtures. The fresh and mechanical properties were studied. It was concluded that an economical SCC with the targeted fresh and mechanical properties can be attained by using FA, S or VMA.

The objective of this research is to study the effect of using RAP and SCMs on the fresh, hardened, and durability characteristics of self-consolidating concrete and the variation of its properties compared to using natural materials.

I. EXPERIMENTAL PROGRAM

A total of 16 mixtures were prepared for the study with different proportions of FA, SL, and combination of both FA and SL as partial replacement for cement and different proportions of RAP in partial replacement for NCA. Four different groups were adopted in this study divided based on the percentage of RAP (0%, 15%, 30%, and 55%). Each group was further divided into four mixtures based on the percentage of SCMs replacing cement (60% FA, 60% S, 30% FA+30% S). Table 1 shows the mixture matrix adopted in this study. Moreover, high range water reducer admixtures (HRWRA) and viscosity modifying agents (VMA) will be used to increase workability and enhance viscosity without compromising the strength and durability of concrete mixtures. Table 2 shows the constituents of SCC mixtures prepared and tested. Following the casting of these mixes, concrete specimens were evaluated by different tests as follows:

Testing: Tests were conducted on both fresh concrete as well as hardened specimens. The different tests included:

a) Fresh concrete: flowability, passing ability, viscosity and the resistance of concrete to segregation, were tested using slump flow test, slump flow with J-Ring, T50, and segregation index tests.
b) Hardened concrete: compression strength tests were conducted on concrete specimens at 3, 14 and 28 days, and split tensile test at 28 days from concrete casting.
c) Durability Characteristics: unrestrained shrinkage test up to 90 days, and rapid chloride permeability test at 45, and 90 days.

Table.1: SCC Mixtures Matrix

Mix Proportions	0% RAP	15% RAP	30% RAP	55% RAP
100% Cement	Mix 1	Mix 5	Mix 9	Mix 13
60% FA +40% cement	Mix 2	Mix 6	Mix 10	Mix 14
60% SL + 40% Cement	Mix 3	Mix 7	Mix 11	Mix 15
30% FA + 30% SL + 40% Cement	Mix 4	Mix 8	Mix 12	Mix 16

2.1 Materials

Crushed limestone constituting of different percentages of material passing through sieve sizes measuring 19 mm (40%), 12.5 mm (20%), 9.5 mm (20%) and 4.75 mm (20%) and well-graded sand were used in the preparation of all mixtures. A relative specific gravity of 2.68 and absorption of moisture at saturated surface dry condition of 1.2% were adopted for the coarse aggregate. For fine aggregates a relative specific gravity of 2.44 and absorption of moisture at saturated surface dry condition of 2.50% were used. Table 3 shows the gradation of the coarse and fine aggregates used in this study. Type I Portland cement having a specific gravity of 3.15 and in accordance with ASTM requirements was used in the development of all concrete mixtures. Class C FA and SL were used as substitutes for cement. To achieve reduced water cement ratio in concrete mixtures, superplasticizer was used and to alter the viscosity, VMA was added to the mixtures to

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achieve the proper viscosity based on the level ofsegregation. RAP was obtained from Illinois Department of Transportation office (IDOT) in Peoria, IL, to ensure its quality. RAP was also sieved using the same sizes used for NCA to ensure overall coarse aggregate homogeneity.

Table.2: Proportions of SCC mixes

MIX #	Cementitious Materials (kg)				W/C Ratio	Water (Kg)	Aggregates (kg)		
	CM	C	FA	SL			RAP	CA	FAG
Mix 1	375	375	0	0	0.4	150	0	865	880
Mix 2	375	150	225	0	0.4	150	0	865	880
Mix 3	375	150	0	225	0.4	150	0	865	880
Mix 4	375	150	112.5	112.5	0.4	150	0	865	880
Mix 5	375	375	0	0	0.4	150	129.75	735.25	880
Mix 6	375	150	225	0	0.4	150	129.75	735.25	880
Mix 7	375	150	0	225	0.4	150	129.75	735.25	880
Mix 8	375	150	112.5	112.5	0.4	150	129.75	735.25	880
Mix 9	375	375	0	0	0.4	150	259.5	605.5	880
Mix 10	375	150	225	0	0.4	150	259.5	605.5	880
Mix 11	375	150	0	225	0.4	150	259.5	605.5	880
Mix 12	375	150	112.5	112.5	0.4	150	259.5	605.5	880
Mix 13	375	375	0	0	0.4	150	475.75	389.25	880
Mix 14	375	150	225	0	0.4	150	475.75	389.25	880
Mix 15	375	150	0	225	0.4	150	475.75	389.25	880
Mix 16	375	150	112.5	112.5	0.4	150	475.75	389.25	880

FAG = fine aggregate

Table.3: Aggregate Gradation

Fine Aggregate		Coarse Aggregate	
Sieve Size (mm)	**%Passing**	**Sieve Size (mm)**	**%Passing**
9.5	100	25	100
4.75	98	19	97
2.36	84	12.5	30
1.18	68	9.5	10
0.6	54	4.75	3
0.3	21	2.36	0
0.15	5	1.18	0
0.075	1	0.3	0

2.2 Testing Methodology:

The testing conducted in this study included freshproperties using slump flow, slump flow with J-ring, T50 test, and segregation index (*SI*) test; hardened properties such as the compressive strength at 3, 14, and 28 days, and the tensile strength at 28 days; and durability characteristics including unrestrained shrinkage strain up to 90 days and rapid chloride permeability test at 45 and 90 days to ensure full hydration of SCC mixtures. All specimens were prepared according to ASTM guidelines.

2.2.1 Fresh Properties

2.2.1.1 Slump flow test and J-Ring test:

The flowability of all mixtures was measured using the slump-flow and T50 tests. The test uses an inverted slump cone as per ASTM C 1611. The inverted cone is filled to its top with concrete. No rodding or vibration was carried out once the concrete is poured in the inverted cone. The cone is then lifted vertically and the spread of the concrete is measured. The average of two perpendicular diameters is taken and considered as the slump flow value. In the J-Ring test, the same procedure of the slump flow test is repeated; however the concrete flow is obstructed using a J-Ring which simulates the rebar on the field to measure the passing ability of the mixtures. All mixtures were required to have acceptable flow ability and workability between 500 and 750 mm and T50 value less than 7s (EFNARC 2005).

2.2.1.2 Segregation Index:

Super plasticizers are added to increase the workability of the mixtures. However, this may result in segregation in the mixtures due to concrete high flow ability. This might occur due to the separation of the aggregate from the mortar mix. Segregation is a common problem and should be avoided since it leads to a major loss in concrete's strength. The segregation index (*SI)* test is used to detect the segregation in SCC mixtures. The concrete patty was visually inspected and rated as follows: a)no clear accumulation of coarse aggregate particles in mortar and no visual segregation, *SI* = 0, b)If there is an apparent accumulation of coarse aggregate in the center of the spread, that means the concrete is assumed to have adequate resistance to segregation, *SI* = 1, c) In case of large accumulation of coarse aggregate or flow of free water, *SI* = 2 and the concrete will likely segregate. Table 4 illustrates the results obtained for the segregation index test for all 16 mixtures studied.

Table.4: Segregation Index Test Results

Mix	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Segregation Index	0	1	2	0	0	1	1	0	2	0	0	1	0	0	0	1

2.2.2Hardened Properties:

Following pouring concrete, it was moist cured in the curing room at room temperature and a relative humidity of 95% until the day of testing.Compressive strength tests were conducted on 100 x 200 mm concrete cylinders at 3, 14 and 28 days according to ASTM (C39/C39M-09), and split tensile strength tests were conducted on 150x300mm cylindersat 28-days according to ASTM (C 496/ C 496M-04).

2.2.3 Durability Characteristics:

2.2.3.1Unrestrained Shrinkage Test:

A 76.2x 76.2x254mm concrete prism cast from each mixture was used to determine theunrestrained shrinkage. These were cured at room temperature and a relative humidity greater than 95% for first 7 days and air-cured after that. The unrestrained shrinkage was measured after 7 days and every 5 days during the air curing phase until 90 days according to ASTMC(490/C490M-09).

2.2.3.2 Rapid Chloride Permeability Test:

The objective of the rapid chlorideperme ability test is to assess the resistance of concrete to chloridepenetration through electrical conductivity measurements. The test is carried out in accordance with ASTM (C 1202-12). Two cylinders of size 100x200 mm were used from each concrete mixture for this test. One cylinder was tested at 45 days and the other at 90 days. A100 mm diameter and 50 mm thickness cylindrical concrete specimen was cut from the tested cylinder and subjected to a 3%sodiumchloride (NaCL)on one side and 0.3 N sodium hydroxide(NaOH) solutions on theotherside.A60-voltcurrentisinduced through the specimen for 6 hours and the current accumulated over time is measured in coulombs.

II. RESUTLS AND DISCUSSIONS

3.1 Fresh Mixed Concrete

For a concrete mixture to be classified as SCC there are certain standards and specifications that need to be fulfilled. The slump flow should be in between 500 mm and 750 mm, and the mixture should have adequate passing ability under its own weight. This is verified by testing the mixture using a J-Ring. Table 5 summarizes the properties of fresh concrete which is measured as soon as the concrete is mixed.

The results show that as the Portland cement is replaced with SCMs, the workability of the mixtures increased significantly. When cement solely was used as a binding material in the mixture, the slump flow was 546 mm for Mix 1 (100% cement, 0% RAP), whereas the slump flow was 673 mm which corresponds to the highest measured slump for Mix 16 (30% FA + 30% SL, 60% RAP).

It is also noticed that as the amount of RAP is increased in the concrete mixtures, the workability and the flowability increased accordingly. In most cases, the binary mixture (40% cement + 60% SL) and the ternary mixture (40% cement + 30%FA+30%SL) are more influential in increasing the slump flow and slump flow with J-Ring compared to the use of (40% cement + 60% FA), which indicates that slag is more effective in improving the workability of SCC mixtures compared to FA. Table 5 shows that replacing natural aggregates with different proportions of RAP increased the inverted slump flow and

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slump flow with J-ring values. However, the amount of HRWRA and VMA used to prepare SCC mixtures were not constant. Although, the amount of HRWRA decreased by 4, 6.7, and 20% for Mix5 (15% RAP +100% cement), Mix 9 (30% RAP+100% cement), and Mix 13 (55%RAP+100% cement) compared to Mix 1 (0% RAP+100% cement), the amount of VMA increased by 50%, 16.7%, and 41.7%, respectively.

Table.5: Fresh Concrete Properties

SP = super plasticizers VMA = Viscosity modifying agent

MIX #	Inverted slump test (mm)	Slump flow with J-Ring (mm)	SP (ml/m3)	VMA (ml)
Mix 1	546	521	450	72
Mix 2	541	516	360	84
Mix 3	597	546.1	450	84
Mix 4	572	521	390	78
Mix 5	599	549	432	108
Mix 6	610	559	540	126
Mix 7	635	584	480	108
Mix 8	630	579	300	90
Mix 9	635	584	420	84
Mix 10	632	597	510	84
Mix 11	635	597	450	102
Mix 12	671	622	450	90
Mix 13	635	584	360	102
Mix 14	643	584	450	84
Mix 15	638	584	480	84
Mix 16	673	648	468	90

3.2 Hardened properties of concrete

The compressive strengths of all mixtures are shown in Fig 1.The compressive strength of the specimens was evaluated at 3, 14, and 28 days. From Fig1, it can be deduced that mixtures incorporating RAP have smaller compressive strength values at 28 days. Mixes 5, 9, and 13are lower in strength by 9.8, 20.9, and 30.6% compared to the Mix1. A similar trend was observed for the binary and ternary mixtures including FA, SL, and FA and SL. Mixtures 6, 10, and 14 are lower in strength by 9.1, 28.5, and 39.3% compared to Mix2. Additionally, Mixtures 7,11, and 15 are lower in strength by 6.0, 20.2, and 35.4% compared to Mix 3. Mixtures 8, 12, and 16 are lower in strength by 21.1, 29.9, and 45.9 compared to Mix 4. Furthermore, the binary mixture including (60% SL+40% cement) experienced less reduction in strength compared to mixtures containing FA and a combination of FA and SL in most cases.This reduction in strength can be attributed to the weak bond between aggregate and asphalt-mortar in RAP.

It can be observed that the increase in strength of concrete in the first three days and in the subsequent 14 days is practically 82% of the 28 days compressive strength for the control mixture (Mix1). Thus, it can be concluded from the results that most of the concrete strength is achieved in the first 14 days and the increase in the strength at 28 days is less significant.

To monitor the effect of RAP, FA, and S and age on the compressive strength of SCC mixtures, a mathematical model using linear regression analysis along with analysis of variance (ANOVA) was studied.

$$\text{Compressive strength} = \text{Constant} + (A \times \text{RAP content}) + (B \times FA) + (C \times SL) + (D \times \text{age}) \quad \text{Equation 1}$$

The results obtained from the regression analysis are shown in Table 6. It is observed that all the studied factors are influential in determining the compressive strength since their p-values are less than 0.05 with R-squared value of 94.27 %. All factors have negative coefficients (-0.03357, -0.03691, -0.0207) indicating a negative impact on the compressive strength development with the exception of age which has a positive coefficient of 0.691.

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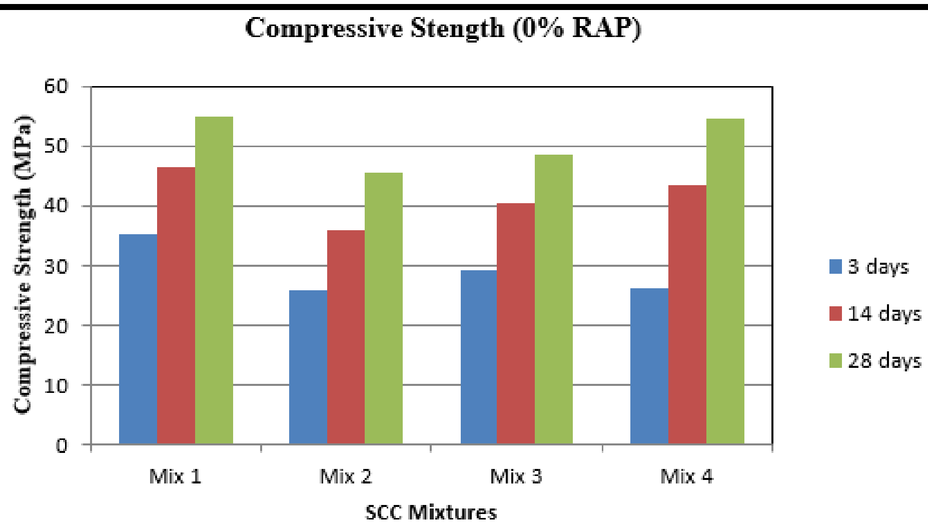

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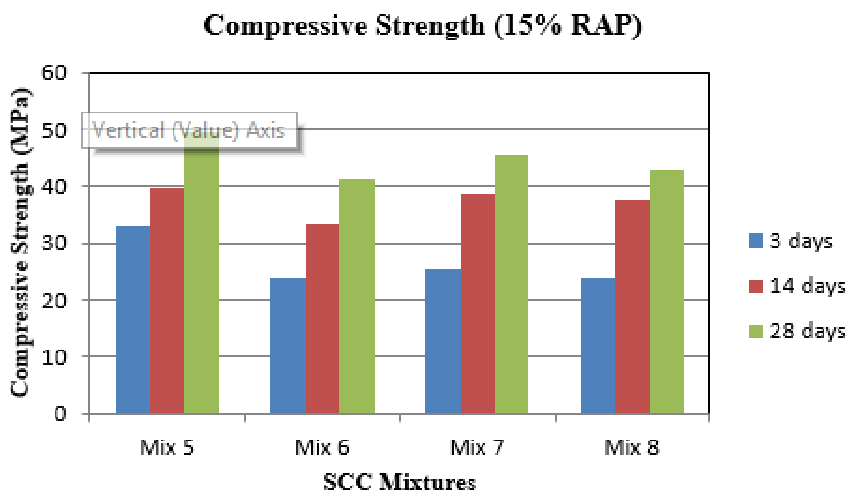

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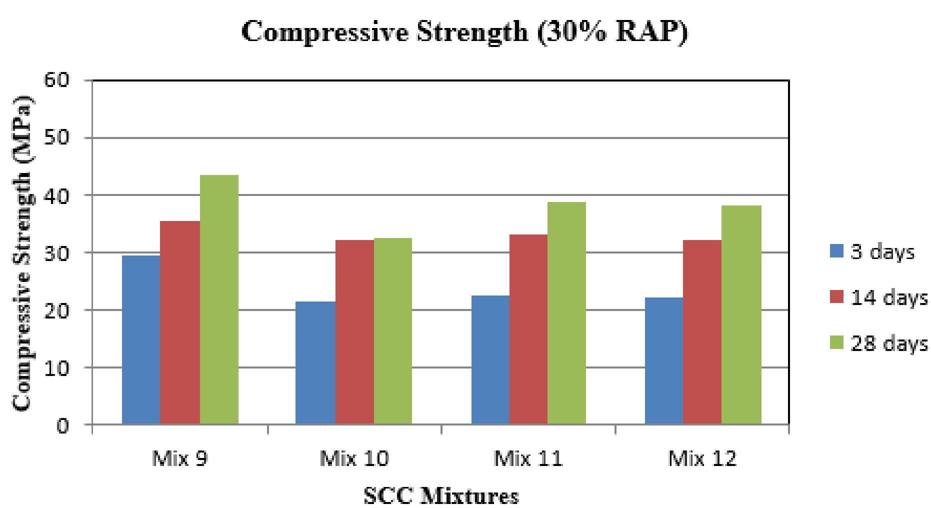

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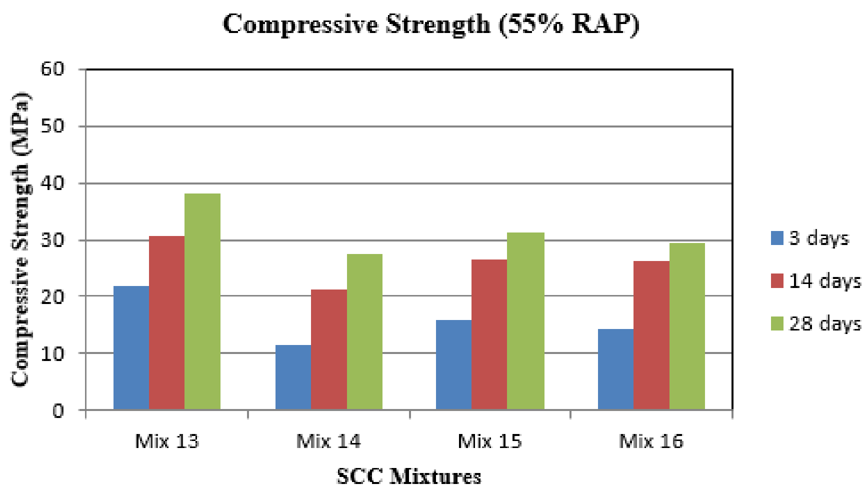

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Fig.1: Compressive Strength of all Mixtures (a) 0% RAP (b) 15% RAP (c) 30% RAP, and(d) 55% RAP.

Table.6: Linear regression model parameters

Factors	Coefficients	Standard Error	t Stat	P-value
Constant	35.02708223	1.01097313	34.6469	4.73544E-33
RAP	-0.03357097	0.002078549	-16.1512	7.18338E-20
Fly Ash (FA)	-0.036919753	0.004394975	-8.40045	1.29394E-10
Slag (SL)	-0.020704938	0.004394975	-4.71105	2.59237E-05
Age	0.691064889	0.035693083	19.36131	7.45698E-23

Fig 2 shows the variation between measured compressive strength versus estimated values predicted by the regression model. A close fit between the measured and estimated compressive strength values was evidenced.

The split tensile strength values are illustrated in Fig3, which clearly demonstrates that the tensile strength of the specimens decreased as the amount of RAP increased which indicates that split tensile strength is inversely proportional to the increase in the amount of RAP in the mixtures regardless of the binder used. With 15% RAP replacing NCA (Mix 5), the strength was reduced by 14% compared to the strength of the control mix (Mix1). Similarly the strength of the mix having 30% RAP (Mix 9) was about 70% of the control strength (Mix1), whereas the mixture having 55% RAP (Mix 13) was only 60% of the strength of the control mixture (Mix1). A similar trend was observed for the mixtures including 60% FA and 60% SL and a combination of FA and SL (30% FA+30% SL). However, the mixtures incorporating 60% SL had lesser reductions in strength in most cases compared to the control mixtures within each of the four groups. The decrease in tensile strength as the percentage of RAP replacing NCA increases is due to the weak bond between the aggregate and the asphalt-mortar surrounding it. The maximum tensile strength recorded corresponded to Mix 1(0% RAP+100 cement) and the lowest to Mix 14 (55% RAP+60% FA).

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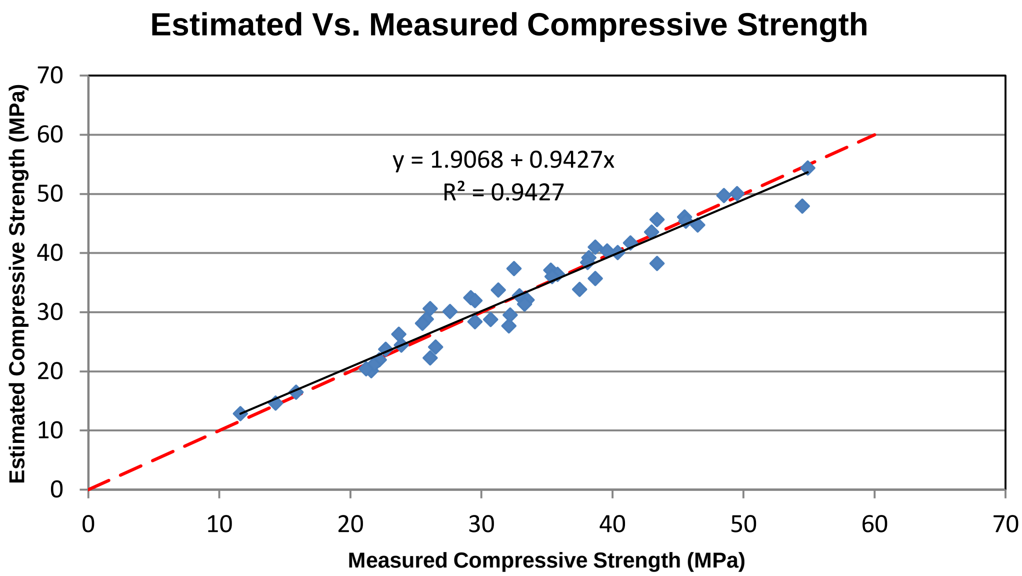


Fig.2: Relationship between Estimated versus Measured Compressive Strength.

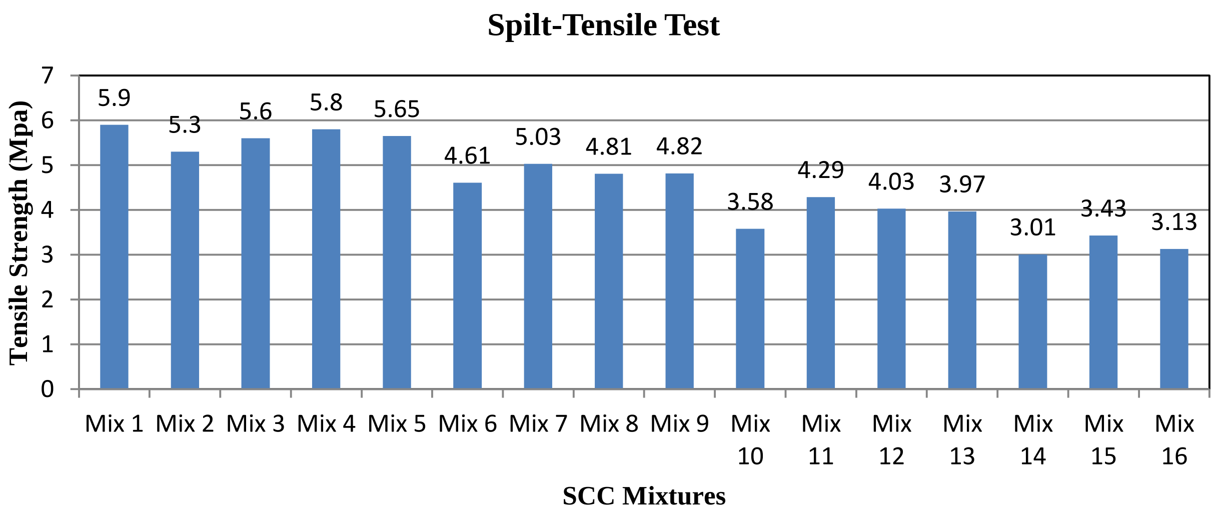


Fig.3: Split Tensile Strength of All SCC Mixtures

3.3 Unrestrained Shrinkage Strain

To study the effect of RAP and SCMs on the durability characteristics of SCC, shrinkage tests were conducted. The shrinkage strain history was measured using a prism from each mixture. The specimen was kept in the curing room for 7 days prior to air curing and the shrinkage strain in each prism was measured every 5 days thereafter. It is observed from the results that using 60% SL as replacement for cement in concrete results in a significant reduction in the shrinkage of concrete as shown in Figs 4 and 5. Mixtures 3, 7, 11, and 15 experienced reductions in their total shrinkage strain by 10.4, 16.7, 4, and 1.58% compared to their control mixtures within each of the four groups (Mix 1, Mix5, Mix 9, and Mix 13). However, this was not the case for the mixtures containing 60% FA or 30% FA and 30% SL replacement where the shrinkage strain increased compared to the control mixtures within each of the four groups and compared to mixtures containing 60% SL as a replacement for cement. This is might be due to the high percentage of FA used in this study (60% FA compared to the usual replacement percentage of 20-30%). In general higher percentages of SL can be used in concrete since its chemical composition is closer to cement than FA, and hence its usage with high percentages (60%) can reduce the concrete shrinkage.

Figs 4 and 5showthat as the amount of RAP replacing NCA increases in the mixtures, the shrinkage strain decreases. Mixtures 5, 9, and 13 have lower shrinkage strain compared to Mix 1 by 2.2, 29.1, and 22.8%. This can be ascribed to the existence of the asphalt binder surrounding the aggregate in RAP which could reduce the porosity of the mixtures containing RAP.

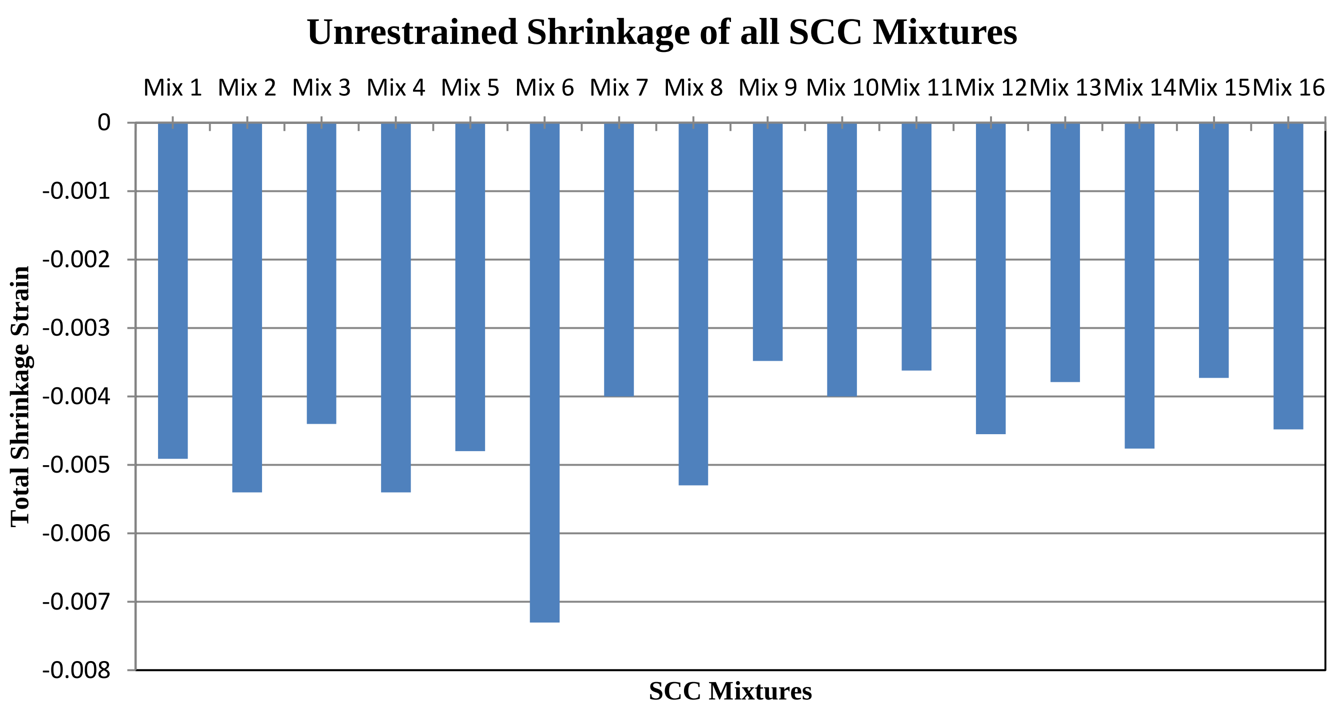
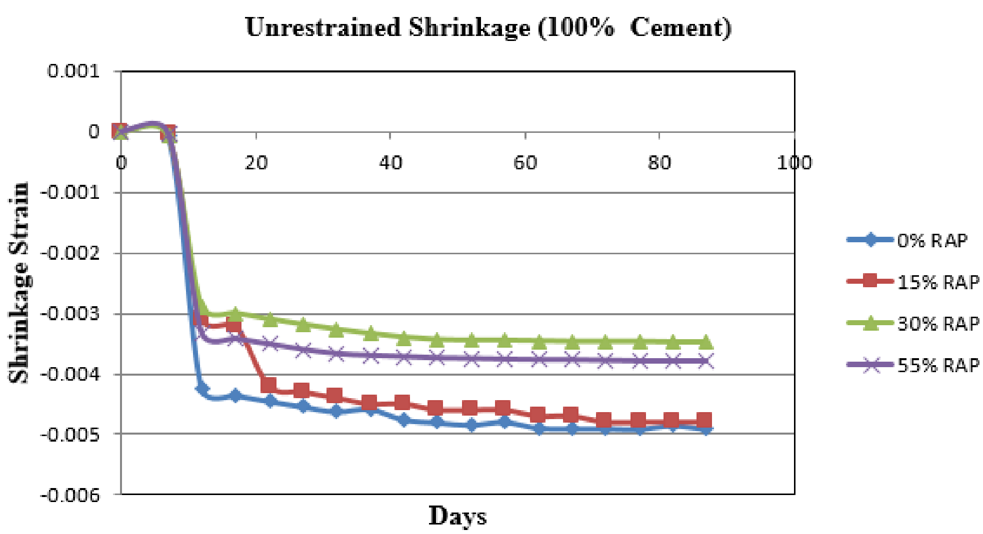


Fig.4: Total Unrestrained Shrinkage of all SCC Mixtures



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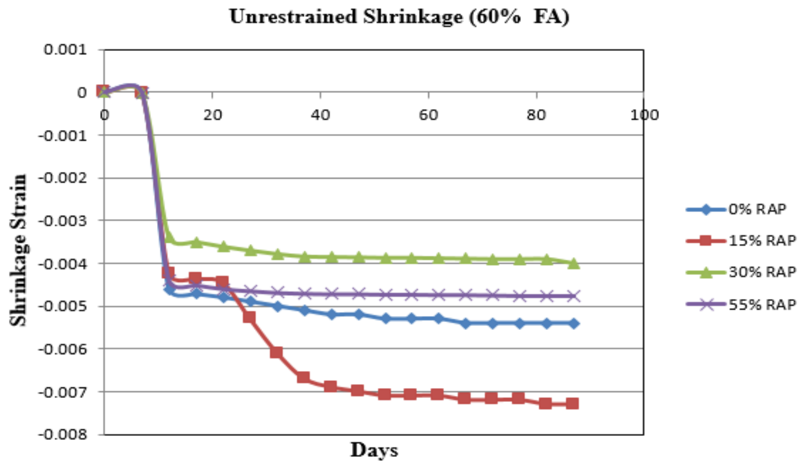

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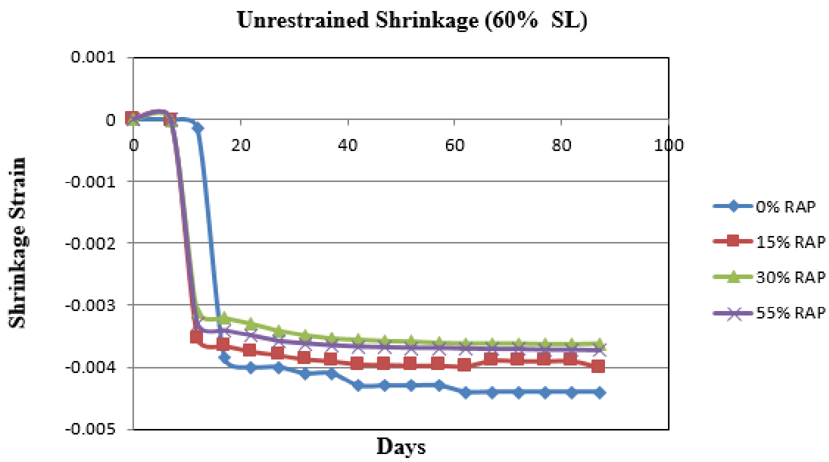

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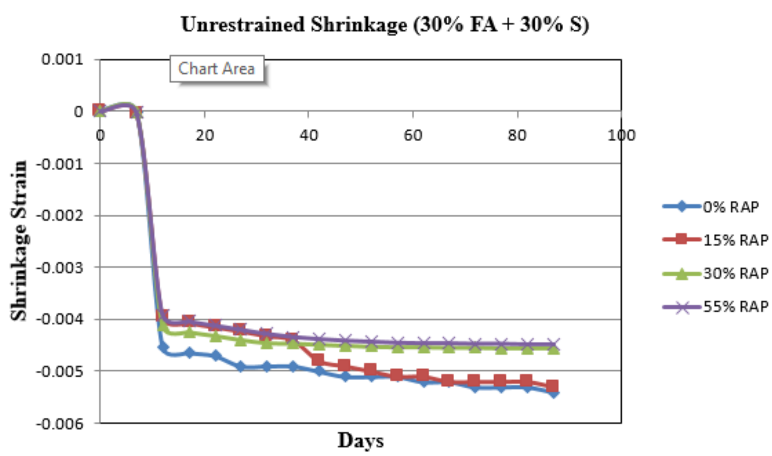

(d)

Fig.5: Free Shrinkage for different binding materials (a) cement, (b) fly ash, (c) slag, and (d) fly ash and slag.

3.4 Rapid Chloride Permeability Tests (RCPT)

Permeability of concrete mixtures was verified using the rapid chloride permeability tests. Due to slow hydration of the mixtures the tests were done at 45 and 90 days. From the tests it is clear that the mixtures with higher RAP content have a higher resistance to chloride penetration when compared to the control mixture within the first group (Mix1). Mixtures 5, 9, and 13 had lower chloride diffusion by 16.8, 30.4, 49.5 % compared to Mix1. This is due to the asphalt binder surrounding the RAP which results in less permeability.

Additionally it is clear that the addition of 60% SL in mixtures 3, 7, 11 and 15 results in a better resistance to chloride penetration when compared to their corresponding control mixes (Mix1, Mix5, Mix9, and Mix13) as shown in Fig6.In general, the control mixtures(100% cement)had less resistance to permeability compared to the other mixtures within each of the four groups (60% FA, 60% SL, and 30% FA+30% SL) which indicates that the use of SCMs reduces the permeability of the SCC mixtures.

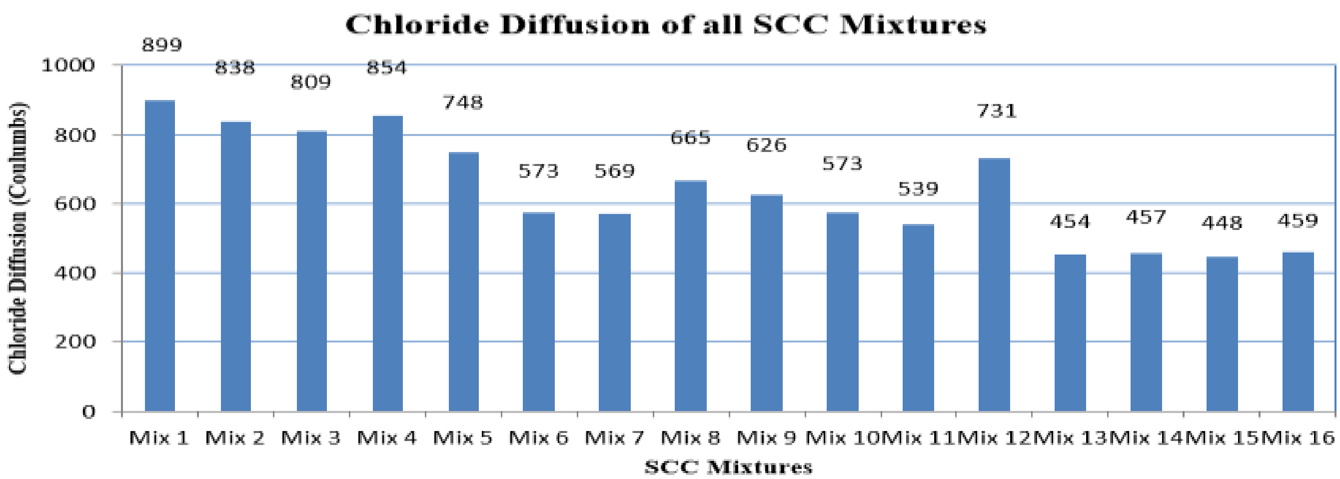

Fig.6: Rapid Chloride Permeability Test for all SCC Mixtures.

III. CONCLUSIONS

A total of sixteen mixtures were prepared and tested, with water to cementations ratio of 0.4 and up to 60% replacement of Portland cement by other supplementary cementations materials which included FA and SL. The fresh properties of the concrete as well as the hardened and durability characteristics conducted in this study which included inverted slump flow tests with and without J-ring, T50, segregation index test, compressive and split tensile strength tests and unrestrained shrinkage and permeability tests. It was apparent from the experiments that the compressive strengths as well as the split tensile strengths of the concrete were reduced as the amount of RAP increased. However the increase in the RAP content improved other properties of the SCC mixtures tested such as permeability resistance. Based on the experimental program conducted in this study, it may be concluded that:

- About 60% FA and 60% SL can be utilized as a part of SCC concrete mixtures as fractional substitution of Portland cement and still produce a workable concrete with high strength and durability.
- Using 15, 30 and 55% RAP which correspond to (Mix 5, Mix9, Mix 13) reduced the 28-days compressive strength of SCC mixtures by 9.8%, 20.9% and 30.6%, compared to the control mix (Mix1) having 0% RAP content.
- As the rate of RAP replacing NCA increased (0-55%), the split tensile strength was reduced.
- The utilization of 60% FA as a substitution for cement resulted in a more significant decrease in the split tensile strength of all mixtures when compared with 60% SL.
- Concrete mixtures containing 60% FA had the most total free shrinkage values when compared with all different mixes including those with 100% cement, 60% SL, and 30% FA and 30% SL.
- As the rate of RAP substitution of NCA increased (0% to 55%) the resistance of SCC mixes to chloride particle infiltration increased as well.
- SCC mixes including high volume of SCMs outperformed their control mixtures within each of the four groups and demonstrated higher imperviousness to chloride infiltration.
- It is evidential that RAP can be used as an effective replacement for coarse aggregate. It is not only cost effective but also can improve the properties of the mixture in some cases.

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