Journal of Building Engineering 12 (2017) 282–287

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Self-compacting concrete using recycled asphalt pavement and recycled concrete aggregate

Yasser Khodair*, Luqman

Department of Civil Engineering and Construction, Bradley University, 1501 West Bradly Avenue, Peoria, IL 61625, United States

ARTICLE INFO

Keywords:
Self-consolidating concrete
Recycled asphalt pavement (RAP)
Recycled concrete aggregate (RCA)
Supplementary cementitious materials
Fly-ash and slag

ABSTRACT

In this study recycled concrete aggregate (RCA) and recycled asphalt pavement (RAP) are used in the production of self-consolidating concrete (SCC) with varying percentage replacements of natural coarse aggregate (NCA). A total of 16 concrete mixtures were prepared and tested. Mixtures were divided into four different groups, with constant water to cementitious (w/cm) material ratio of 0.4, based on RCARAP content: 0%, 25%, 50%, and 75% of NCA replaced by RCARAP. Portland cement was used for the control mixtures of each group, while all other mixtures were designed with partial replacement of cement by supplementary cementitious materials (70% fly-ash, 70% slag, and 25% fly-ash + 25% slag). The fresh properties such as flowability, deformability; filling capacity, and resistance to segregation of concrete were investigated. The hardened properties such as compressive strength and split tensile strength were studied. The durability characteristics including the unrestrained shrinkage test, and rapid chloride permeability test (RCPT) were investigated. Partial replacement of cement using FA and S resulted in smaller 28-days-compressive strength compared to control mixtures. The replacement of NCA by RCARAP reduced the workability, and the compressive and tensile strengths of SCC mixtures.

1. Introduction

One of the most advanced developments in concrete technology is self-consolidating concrete (SCC) and it is one category of high performance concrete (HPC). SCC was first developed by Japanese researchers [1]. There was extreme demand of narrow highly reinforced concrete mostly at beam-column joints. The use of SCC will result in reduction of labor cost since it eliminates mechanical vibration and speeds the construction process [2]. The use of low slump traditional concrete in congested zones without skilled labors may cause serious problems such as porous concrete, and weak bonding. Partial replacement of Portland cement by SCMs can enhance the workability of SCC. In order to overcome some of the problems associated with SCC, many researchers have studied the use of SCMs, [13]. Bouzoubaa et al. [3] studied the properties of SCC in which the cement was replaced by class F Fly ash. Nine SCC mixtures and one control concrete mixture was prepared and tested. The effect of replacing Portland cement by 40%, 50% and 60% class F Fly ash was studied. The SCMs content was fixed at 400 kg/m^3 and water/cement ratio ranged from 0.35 to 0.45. Several tests were conducted to study the fresh properties of SCC mixtures. It was concluded that fly ash slightly improves the concrete workability and compressive strength.

Bermel et al. [4] studied the usage of RAP concrete for pavement in Montana. In order to use RAP as replacement for natural aggregates, many mixes with dissimilar proportions were made for Portland cement concrete pavement (PCCP). Tests were conducted to find the related property of RAP concrete to be used in PCCP. It was observed that use of traditional practices concrete containing RAP aggregate up to 25% fine and 40% coarse replaced aggregate can give compressive strength of more than 25-Mpa. When the amount of RAP replacing natural aggregate increased, there was a decrease in the compressive strength. There was more benefit observed when both fine and coarse aggregate were replaced by RAP when compared to only one replacement. It was also observed that RAP concrete displayed more flexural strength to that of conventional Portland cement concrete.

The use of RCA was also studied by several researchers. Khayat [5], investigated the workability requirements for self-consolidation and discussed the use of several tests that can be utilized to find the capacity of filling, deformability, and stability of SCC. Additionally, the proportioning of SCC mixtures to reduce the amount of coarse aggregate and to increase the workability of SCC mixtures was discussed. Hwang et al. [6] performed an experiment to check the accuracy of different tests to determine the workability and to study usage characteristics of concrete utilized in various applications of structures. Seventy SCC mixtures were evaluated for workability properties made with w/cm that ranged between 0.35 and 0.42. It was concluded that slump flow, J-ring or V-funnel flow time tests can be used to study the suitability of SCC mixtures to fill narrow sections, and SCC mixtures with slump flow

* Corresponding author.

http://dx.doi.org/10.1016/j.jobe.2017.06.007
Received 17 October 2016; Received in revised form 27 May 2017; Accepted 7 June 2017
Available online 13 June 2017
2352-7102/

values that range between 620 and 720 mm are suitable to be used in structural applications.

This study investigates the feasibility of producing SCC including high volume of SCMs, greater than 50%, including RCARAP up to 75% as partial replacement for NCA with adequate properties.

2. Objectives

The main objective is to study the effect of using combined recycled concrete aggregate and recycled asphalt pavement (RCARAP) and supplementary cementitious materials (SCMs) such as fly-ash (FA) and slag (S) on the fresh, mechanical, and durability characteristics of SCC. The partial percentage replacement of NCA with RCARAP were 0%, 25%, 50% and 75%; and cement replaced with 70% FA, 70% S and combination of 25% FA and 25% S in concrete mixtures. There are four SCC mixtures for a particular RCARAP percentage replaced: (1) 0% replacement of cement content (2) 70% cement replacement by FA (3) 70% cement replacement by S and (4) 50% cement replacement by FA and S (25% Fly Ash and 25% Slag).

3. Experimental program

Table 1 summarizes the mixtures matrix used in this study. A total of 16 mixtures were prepared and tested. Four groups were used in this study based on the amount of RCARAP replacing NCA (0%, 25%, 50% and 75%), where each percentage replacement of RCARAP is divided equally between RCA and RAP. Each group consists of four mixtures with different binding materials, where the cement was replaced by different percentages of FA and S (70% FA, 70% S and combination of 25% FA and 25% S) in concrete mixtures. The testing conducted included: (1) the fresh properties of all mixtures tested by determining the slump flow test, passing ability using the slump flow with J-Ring, viscosity of SCC using T50 test and segregation using the segregation index (*SI*) test, (2) the hardened properties of all mixtures using the compressive strength at 3, 14, and 28 days and split tensile test at 28 days, and 3) the durability characteristics using the unrestrained shrinkage and rapid chloride permeability tests (RCPT) tests.

3.1. Materials

Crushed limestone with relative specific gravity of 2.68 and moisture absorption of 1.2% at saturated surface dry (SSD) condition, and RCA with relative specific gravity of 2.39 and moisture absorption at SSD of 3.03% were used in the preparation of all SCC mixtures. The same aggregate gradation was used for NCA, RCA, and RAP used as coarse aggregates (40% passing through sieve size measuring 19 mm, 20% passing through sieve size 12.5 mm, 20% passing through sieve size 9.5 mm and 20% passing through sieve size 4.75 mm) to ensure uniformity of the coarse aggregate. RAP from hot mixed asphalt obtained from Illinois Department of Transportation (IDOT), and RCA from local supplier were used in the mixtures. Local sand with relative specific gravity of 2.44 and moisture absorption of 2.5% at saturated surface dry condition was used as fine aggregate. The gradations of the coarse and fine aggregates are shown in Fig. 1. Type I Portland cement having a specific gravity of 3.15, and surface area of 400 m^2/kg was used in the preparation and mixing of all concrete mixtures. Class C FA

Table 1
SCC Mixtures Matrix.

Mixtures Proportions	100% Cement	70% FA	70% S	25% FA + 25% S
0% RCARAP	Mix 1	Mix 2	Mix 3	Mix 4
25%RCARAP	Mix 5	Mix 6	Mix 7	Mix 8
50% RCARAP	Mix 9	Mix 10	Mix 11	Mix 12
75% RCARAP	Mix 13	Mix 14	Mix 15	Mix 16

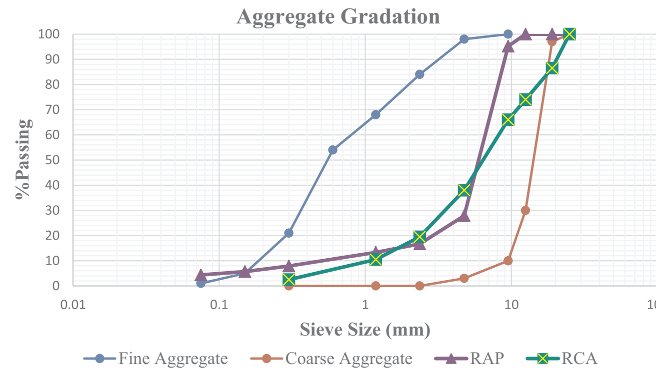


Fig. 1. Natural coarse and fine aggregates gradation.

and S were also used as binding materials with different percentages replacing cement. High range water reducing agent (HRWRA) and viscosity modifying agents (VMA) were used to increase the workability of all mixtures and to enhance the viscosity of SCC mixtures.

3.2. Fresh properties

The fresh properties of SCC such as flowability, and passing ability were measured using the slump flow test according to ASTM C 1611 [7], and slump with J-Ring according to ASTM C 1621 [8]. The segregation resistance of all prepared mixtures was evaluated using the *SI* test. This test relies on visual inspection and each mix was given a value between (0 and 2), where $SI = 0$ indicates no segregation, $SI = 1$ indicates acceptable segregation, and $SI = 2$ denotes significant segregation occurred. The fresh properties of SCC mixtures are shown in Table 2.

3.3. Hardened properties

The hardened properties in this study included testing the average compressive strength of three 100 × 200 mm cylinders, according to ASTM (C39/C39M-09) [9], at 3, 14, and 28 days, the split tensile strength of a 150 × 300 mm SCC cylinder, according to ASTM (C 496/C 496M-04) [10], at 28 days. All specimens were moist cured at a relative humidity of 95% until the day of testing.

3.4. Durability characteristics of concrete mixtures

3.4.1. Unrestrained shrinkage test

A 76.2 × 76.2 × 254 mm concrete prism cast from each mixture was used to determine the unrestrained shrinkage of all concrete mixtures using a Comparator test set-up. The prisms were moist cured in the curing room at room temperature and relative humidity of 95% for the first 7 days and air cured thereafter. The unrestrained shrinkage was measured after 7 days and every 5 days during the air curing phase until 90 days according to ASTM C (490/ C 490M-09) [11].

3.4.2. Rapid chloride permeability test

The rapid chloride permeability test is used to evaluate the resistance of concrete to chloride diffusion. The test was performed in accordance with ASTM (C 1202-12) [12]. A cylindrical plain concrete specimen with a 100 mm diameter and a 50 mm thickness is exposed to a 3% sodium chloride (NaCl) on one side and 0.3 N sodium hydroxide (NaOH) solution on the other side. A 60-volt current is passed through the specimen for 6 h and the current integrated over time is measured in coulombs.

Table 2
Fresh properties of all SCC mixtures.

Mixes	% of SCM	RCARAP (%)	Slump Flow without J-Ring (mm)	T50 without J-Ring (s)	Slump Flow with J-Ring (mm)	T50 with J-Ring (s)	Segregation Index (SI)	HRWRA (ml/m^3)	VMA (ml/m^3)
Mix 1	100% Cement	0%	533	3	508	4	0	592	89
Mix 2	70% FA	0%	533	3	508	4	1	444	104
Mix 3	70% S	0%	609	3	558	4	2	592	104
Mix 4	25% FA + 25% S	0%	584	4	533	6	0	503	104
Mix 5	100% Cement	25%	609	4	533	6	0	555	148
Mix 6	70% FA	25%	635	4	584	6	1	637	148
Mix 7	70% S	25%	635	3	584	5	0	592	148
Mix 8	25% FA + 25% S	25%	635	5	584	7	1	407	111
Mix 9	100% Cement	50%	635	5	584	7	0	481	111
Mix 10	70% FA	50%	635	5	584	7	2	629	111
Mix 11	70% S	50%	609	5	558	6	0	592	118
Mix 12	25% FA + 25% S	50%	685	5	609	7	0	555	111
Mix 13	100% Cement	75%	635	5	584	7	0	578	111
Mix 14	70% FA	75%	635	5	558	8	1	592	111
Mix 15	70% S	75%	635	6	584	8	0	629	118
Mix 16	25% FA + 25% S	75%	685	6	609	8	0	667	118

4. Results and discussion

4.1. Effect of SCMs and RCARAP on the fresh properties of SCC mixtures

Fig. 2 shows that the inclusion of FA and S as replacement for cement increase or at least stabilize the workability of SCC mixtures including those containing RCARAP. The slight increase or no change in the values of the slump flow is due to the different amounts of HRWRA and VMA used in every mixture to meet or exceed SCC minimum slump flow requirements, between 500 and 750 mm, [13]. Another factor could be the high percentages of SCMs, greater than 50%, used in this study. Additionally, as the percentage of RCARAP replacement of NCA increases, the value of slump flow also increases or remains stable for all binding materials: (1) 100% cement in Mixes 1, 5, 9 and 13, (2) 70% FA in Mixes 2, 6, 10 and 14, (3) 70% S in Mixes 3, 7, 11 and 15, and (4) combined use of FA and S (25% FA + 25% S) in Mixes 4, 8, 12 and 16. The reason for the slight or no increase in the slump flow can be attributed to the higher absorption of RCA compared to NCA and RAP, the high viscosity of the asphalt-mortar coating surrounding the aggregate and the angularity of RCA and RAP particles compared to NCA. The highest slump flow value (686 mm) was recorded for Mix 12 (50% RCARAP + 25% FA + 25% S) and Mix16 (75% RCARAP + 25% FA + 25% S), while the lowest slump flow value (533 mm) corresponds to Mix 1 (100% cement + 0% RCARAP) and Mix 2 (70% FA + 0% RCARAP).

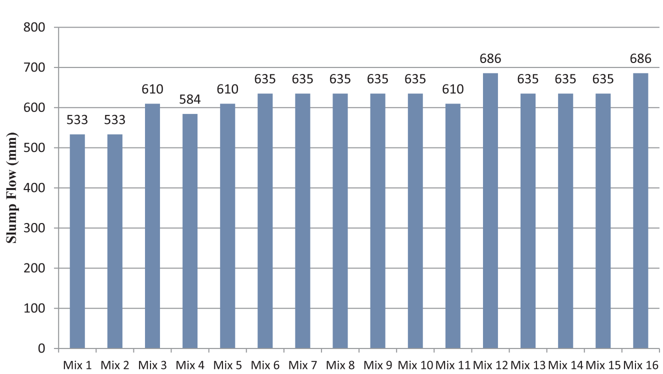


Fig. 2. Slump flow values of all mixtures.

4.2. Effect of SCMs and RCARAP on the hardened properties of SCC mixtures

4.2.1. Effect of SCMs and RCARAP on the compressive strength of SCC

It is clear from Fig. 3a–d, that the use of SCMs instead of cement reduces the compressive strength in all mixtures. However, the decrease in the compressive strength of the mixtures containing only FA is more than those containing S or FA and S. The use of 70% FA in Mixes, 2, 6, 10, 14 reduces the 28-days compressive strength by 17.3%, 16.0%, 25.2%, and 27.6% compared to the control mixes within each of the four groups (Mixes 1, 5, 9, and 13). Additionally, it is shown in Fig. 3 that the use of 70% S has a lesser effect in reducing the compressive strength compared to the ternary mixture (50% cement + 25% FA + 25% S). This reduction in the compressive strength is due to the higher than usual volume of SCMs investigated in this study, which resulted in a reverse effect and produced mixtures with lower compressive strength. Furthermore, as the percentage of RCARAP increases (0% to 75%) the compressive strength of all mixtures decreases accordingly. The compressive strength decreased in Mix 5 (100% cement + 25% RCARAP), Mix 9 (100% cement + 50% RCARAP), and Mix 13 (100% cement + 75% RCARAP) by 11%, 26%, and 43.8%, respectively, compared to Mix 1 (100% cement + 0% RCARAP). A similar trend is observed in all mixtures. Therefore, it can be concluded that the compressive strength of SCC mixtures is inversely proportional to the increase in the percentage of RCARAP replacing NCA. This reduction in strength can be justified by the weak bond between the asphalt-mortar and aggregate in RAP, and the adherence of mortar to the RCA aggregate, which is evidenced by the high absorption of the RCA aggregate. The higher absorption of water can reduce cement hydration and decreases the compressive strength.

To study the effect of the most crucial parameters affecting the compressive strength of SCC mixtures such as RAP, FA, and S and age, a linear regression analysis along with analysis of variance (ANOVA) is conducted.

$$\text{Compressive strength} = \text{Constant} + (a \times \text{RAP content}) + (b \times FA) + (c \times S) + (d \times \text{age}) \tag{1}$$

The results obtained from the regression analysis are shown in Table 3. Each of the factors studied (RCARAP, fly-ash, slag and age) was found to be significant in the development of compressive strength since they all have a p-value less than 0.05 with R-squared value of 94.05%. The regression analysis shows that the age of the mixture has a

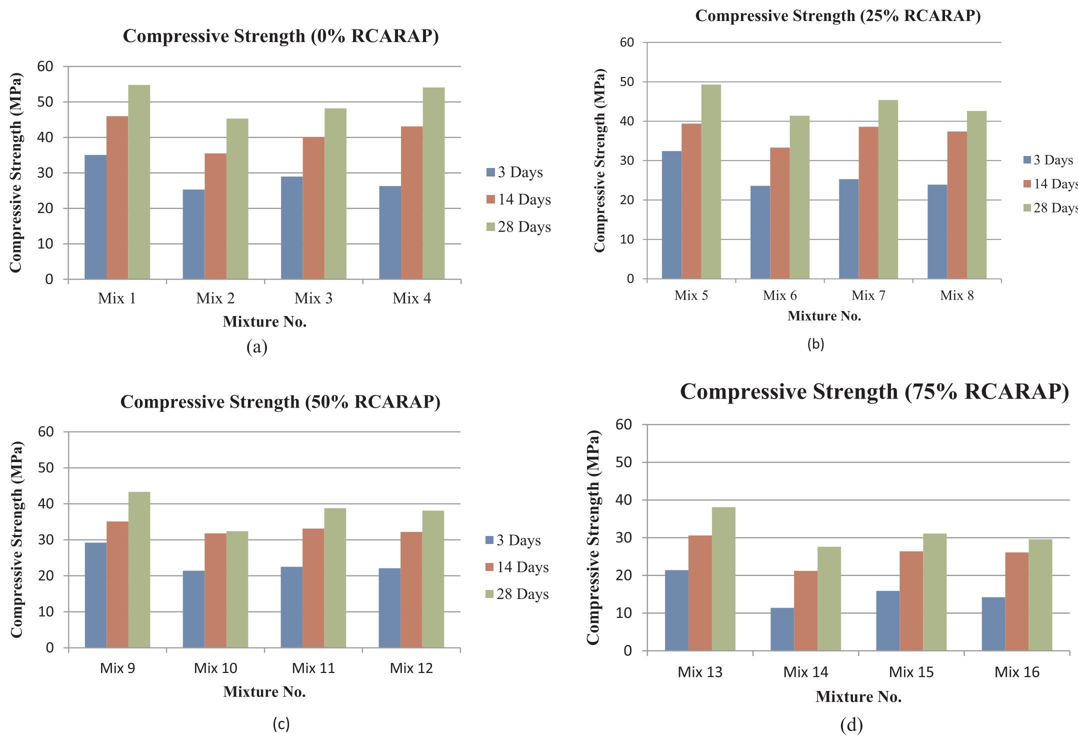


Fig. 3. SCC compressive strength: (a) 0% RCARAP, (b) 25% RCARAP, (c) 50% RCARAP, (d) 75% RCARAP.

Table 3
Linear regression model parameters.

Factors	*Coefficients*	*Standard Error*	*t Stat*	*P-value*
Constant	35.12710173	1.02880028	34.14375	8.69E−33
RCARAP	−0.206643333	0.01325984	−15.5842	2.68E−19
Fly ash	−0.124771083	0.014961166	−8.33966	1.57E−10
Slag	−0.072199655	0.014961166	−4.8258	1.79E−05
Age	0.693519108	0.036226727	19.14385	1.15E−22

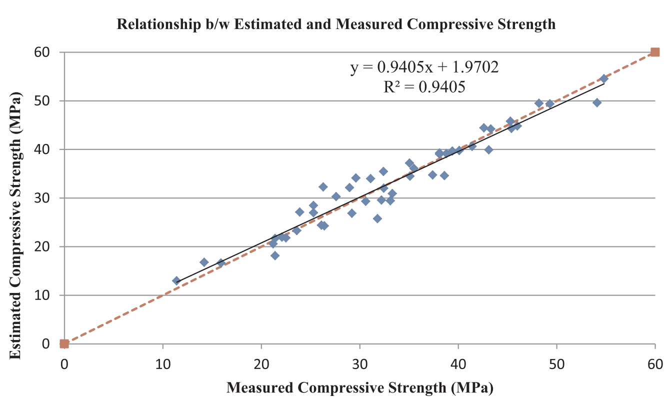


Fig. 4. Estimated versus measured compressive strength for all parameters.

positive impact on the development of compressive strength with a coefficient of 0.6935, whereas the other factors (RCARAP, FA, and S) have negative impact (−0.2066, −0.1247 and −0.0722 respectively) with RCARAP having the most adverse impact on the compressive strength. A comparison of statistical analysis and values obtained from laboratory experiments showed a relevant relationship with all the points being close to equality line. The Comparison of estimated and measured compressive strength is shown in Fig. 4.

4.2.2. Effect of SCMs and RCARAP on the tensile strength of SCC

Fig. 5 shows the split tensile strength of all SCC mixtures prepared

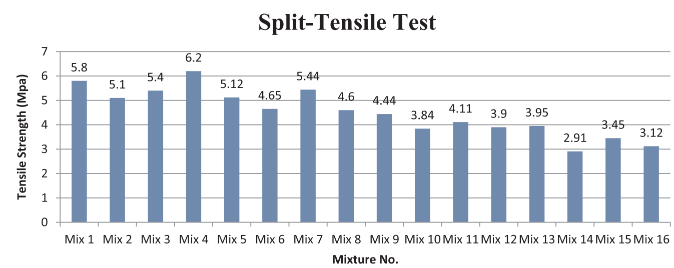


Fig. 5. Split tensile results for all mixtures.

and tested after 28 days. The use of SCMs as a partial replacement for cement reduces the split tensile strength of SCC mixtures with 70% FA being most influential in reducing the strength, followed by 70% S, and a combination of (25% FA + 25% S) with the exception of Mix 4 (0% RCARAP + 25% FA+ 25% S) which has the maximum tensile strength of 6.2 MPa. The minimum tensile strength value was 2.91 MPa for Mix 14 (75% RCARAP + 70% FA). The tensile strength decreases as the percentage of RCARAP increases in the mixtures. The tensile strength decreased by 11.7%, 23.4%, and 31.8% when RCARAP percentage is increased by 25%, 50% and 75% respectively (Mixes 5, 9, and 13) when cement solely is used as a binding material. This can be attributed to the weak bond between the asphalt-mortar and aggregate in RAP, and the adherence of mortar to the RCA aggregate. A similar trend is observed when 70% FA, 70% S, and 25% FA+25% S are used as binding materials in addition to cement.

4.3. Effect of SCMs and RAP on the durability characteristics of SCC-RAP mixtures

4.3.1. Effect of SCMs and RAP on the unrestrained shrinkage

Fig. 6 shows the total shrinkage strain of all SCC mixtures. It is observed that partial replacement of cement with SCMs reduces the unrestrained shrinkage. Control mixtures (Mixes 1, 5, 9 and 13) have the highest shrinkage followed by mixtures with 70% S (Mixes 3, 7, 11 and 15) as binding material, whereas mixtures with 70% FA is most effective in reducing the unrestrained shrinkage of all SCC mixtures.

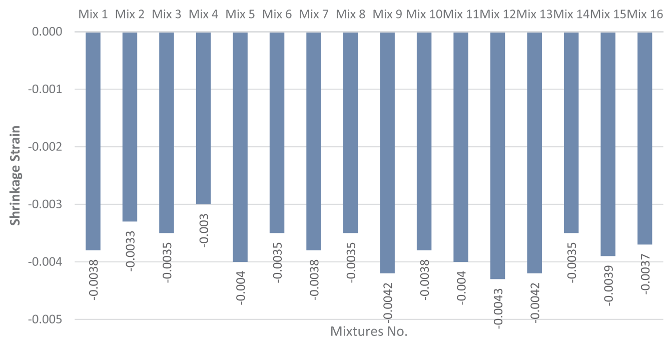


Fig. 6. Total unrestrained shrinkage of SCC mixtures.

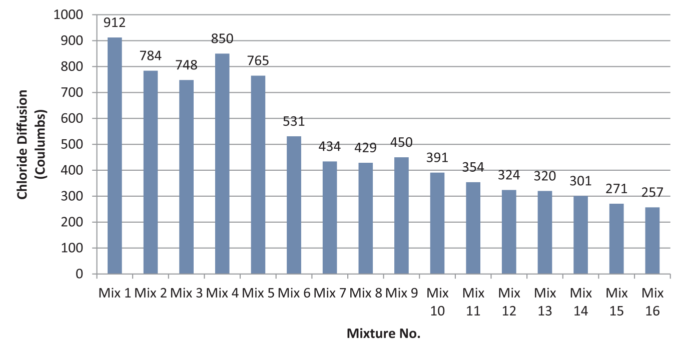


Fig. 8. Chloride diffusion in all SCC mixtures using Rapid Chloride Permeability Test (RCPT).

Furthermore, as the percentage of RCARAP replacing NCA increases, the unrestrained shrinkage increases accordingly which indicates that the RCARAP has more adverse effect on the shrinkage. This can be attributed to the existence of cement paste with RCA and its higher water absorption. The maximum recorded shrinkage (−0.0043) correspond to Mix 12 (50% RCARAP + 25% FA+ 25% S) and the minimum value (−0.0030) corresponds to Mix 4 (0% RCARAP + 25% FA +25% S). Fig. 7a-d shows the unrestrained shrinkage of all mixtures based on the percentage of RCARAP replacing NCA.

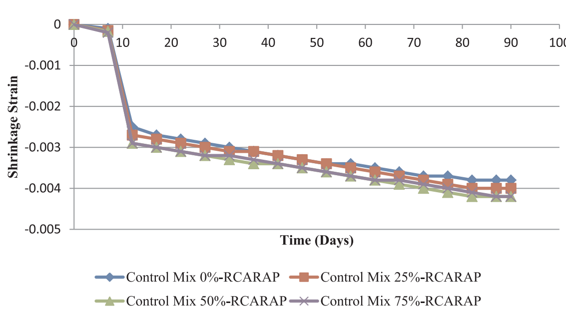
4.3.2. Effect of SCMs and RAP on the Permeability

The permeability resistance of SCC mixtures was measured using rapid chloride permeability test (RCPT) at 90 days. Fig. 8 shows the chloride permeability for all mixtures. It is observed that the use of SCMs reduces the permeability of SCC mixtures. The control mixtures (Mixes 1, 5, 9, and 13) have the highest chloride penetration. Mixtures that contain a combination of 25% FA and 25% S have the lowest permeability when the percentage of RCARAP remains constant with the exception of Mix 3 (0% RCARAP + 70% S) where the measured chloride diffusion is slightly lower than Mix 4 (0% RCARAP + 25% FA +25% S). Additionally, as the percentage of RCARAP replacing NCA increases, the resistance to chloride penetration increases regardless of the binding materials used. This can be attributed to the asphalt mortar and binder surrounding the RAP which is highly viscous in nature and the existence of mortar surrounding RCA, which could result in reducing the size of concrete pores.

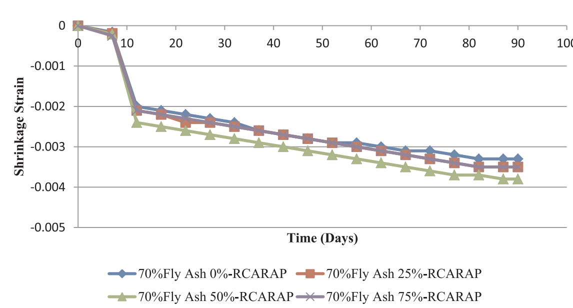
4.4. Summary and conclusions

Four different groups with different RCARAP replacing NCA by 0%, 25%, 50%, and 75% were prepared and tested. Each group has four mixtures with different binding materials (100% Portland cement, 70% FA, 70% S, 25% FA and 25% S). Based on the results obtained from the experimental program, the following conclusion can be drawn:

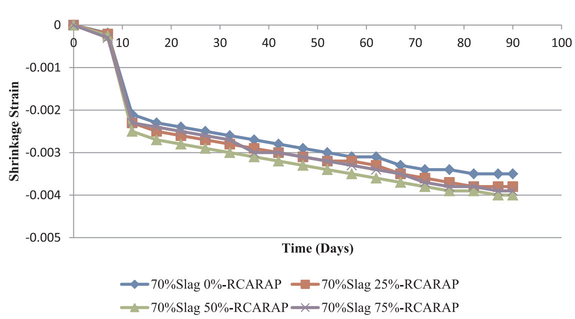
1. A high strength, workable, durable and cost-effective SCC is achieved by using 70% FA and 70% S in concrete mixtures as partial replacement of Portland cement.
2. Using RCARAP as a replacement for NCA with 0%, 25%, 50% and 75% in SCC mixtures resulted in reducing the workability when compared to the control mixtures (Mixes 1, 5, 9, and 13) within each of the four groups studied.
3. The partial replacement of RCARAP for NCA by 25%, 50%, and 75% resulted in reducing the 28-days compressive strength of SCC mixtures.
4. The compressive strength of the SCC mixtures including a combination of 25% FA and 25% S at 28-days was in between those made



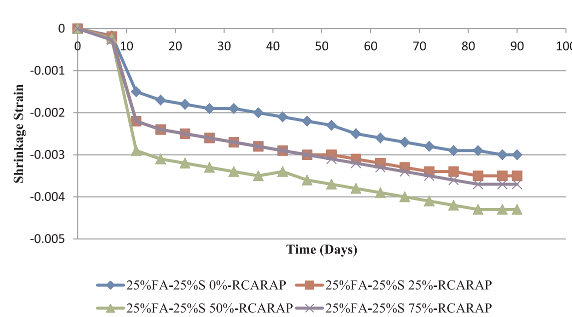
(a)



(b)



(c)



(d)

Fig. 7. SCC Shrinkage: (a) SCC-control, (b) SCC-70% FA (c) SCC-70% S, (d). SCC-25% FA +25% S.

by 70% FA and 70% S with S being higher and FA lower.
5. It can be deduced from the developed linear regression model that age is the only parameter that had a positive effect on the compressive strength of SCC mixtures.
6. The use of RCARAP in lieu of NCA resulted in the decrease of the split tensile strength of all mixtures regardless of the binding materials used.
7. The highest reduction in the split tensile strength of all mixtures corresponded to using 70% FA as partial replacement for cement when compared to mixtures having 70% S and 25% FA and 25% S.
8. The use of SCMs reduces unrestrained shrinkage, whereas the replacement of NCA by RCARAP resulted in the increase of shrinkage.
9. SCC mixtures including high content of SCMs gave better results than their corresponding control mixtures and showed higher resistance to chloride penetration.

References

[1] K. Ozawa, K. Maekawa, H. Kunishima, H. Okamura. Performance of concrete based on the durability design of concrete structures, in: Proceedings of the 2nd East-Asia-Pacific Conference on Structural Engineering and Construction, Vol.1, Chiang Mai, Thailand, 445-456.

[2] K.M.A. Hossain, M. Lachemi, Fresh, mechanical, and durability characteristics of self-consolidating concrete incorporating volcanic ash, J. Mater. Civil. Eng. 22 (7) (2010) 651–657.

[3] N. Bouzoubaa, M. Lashemi, Self-compacting concrete incorporating high-volume of class f fly ash, Cem. Concr. Res. 31 (3) (2001) 413–420.

[4] B. Bermel, Feasibility of Reclaimed Asphalt Pavement as Aggregate in Portland Cement Concrete Pavements, B. Bermel, Feasibility of Reclaimed Asphalt Pavement as Aggregate in Portland Cement Concrete Pavements, M.Sc. Thesis, Montana State University–Bozeman, 2011., Montana State University–Bozeman, 2011.

[5] K.H. Khayat, Workability, testing, and performance of self-consolidating concrete, Acids Mater. J. 96 (3) (1999) 346–353.

[6] Soo-Duck Hwang, KamalH. Khayat, Olivier Bonneau, Performance-Based Specifications of Self-Consolidating Concrete Used in Structural Applications, ACI Materials Journal, V. 103, No. 2, March-April, 2006.

[7] ASTM C 1611/C 1611 M-09b, Standard test method for slump flow of self-consolidating concrete. American Society for Testing and Materials, West Conshohocken, PA, 2009.

[8] ASTM C 1621/ C 1621M-09b. Standard Test Method for Passing Ability of Self-369 Consolidating Concrete by J-Ring, American Society for Testing and Materials, Pennsylvania, 370 PA, 2009.

[9] ASTM C 39/ C39M-10, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, American Society for Testing and Materials, Pennsylvania, PA, 2010.

[10] ASTM C496 / C496M – 11, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens Cement Concrete & Aggregates Australia - CCAA. Use of Recycled Aggregates in Construction. Sydney, Australia: CCAA; 2008 Construction and Building Materials, 22(9), 1963–1971, 2011.

[11] ASTM C 490/C 490M-09, Standard Practice for Use of Apparatus for the Determination of Length Change of hardened Cement Paste, Mortar, and Concrete, American Society for Testing and Materials, Pennsylvania, PA, 2009.

[12] ASTM C 1202-12, Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration, ASTM International, West Conshohocken, PA, 2010.

[13] EFNARC, Specification and guidelines for self-compacting concrete, Association House, Farnham, U.K., 68, 2005.