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Fresh and mechanical properties of roller compacted concrete containing Cationic Asphalt Emulsion admixture

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HIGHLIGHTS

- RCC mixtures containing Cationic Asphalt Emulsion admixture were investigated.
- OMC, MDD, workability and compactability by gyratory compactor were compared.
- Compressive, splitting tensile and flexural strengths of RCCs were evaluated.
- One/two-way ANOVA to assess significance of results' difference was applied.
- The SEM images were employed to interpret the results.
- 4% of CAE can reduce compaction energy required to reach satisfactory density.

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ABSTRACT

This research aims at evaluating the fresh and mechanical properties of RCC mixtures containing Cationic Asphalt Emulsion (CAE) as an admixture (0%, 2%, 4%, 6%, 8%, and 10% of the cement mass). Mixtures' proportions were obtained for each RCC mixture by calculating the maximum value on moisture-dry density curve according to modified proctor method. Then, Optimum Moisture Contents (OMC) and Maximum Dry Densities (MDD) were compared among the mixtures. Fresh properties of the RCC mixtures were also evaluated by Superpave Gyratory Compactor (SGC) while compressive strength, splitting tensile strength and flexural strength tests were employed for investigating the mechanical properties of the mixtures. Non-destructive ultrasonic test was performed in each cubic specimen to develop the compressive strength estimation model. Significance of the results' difference in each test considering the CAE content and curing age as sources of variance was assessed through Analysis of Variance (ANOVA) at 95% confidence level. Results indicated a significant improvement in fresh properties, and a significant drop in the mechanical properties when CAE is used as an admixture. In addition, Scanning Electron Microscope (SEM) images were used to evaluate the micro-structure of the mixtures. Results of this research indicate that 4% of CAE can reduce the amount of compaction energy required to reach the satisfactory field density. This improvement in fresh properties can decrease execution costs and lead to time saving. Furthermore, results of the mechanical tests indicate a reduction in mixture strengths due to the decreased cohesion between cement paste and the asphalt covered aggregates.

1. Introduction

RCC is known to be a proper option for construction of those pavements that are exposed to heavy and frequent loads. Since it doesn't need any reinforcement or forms, RCC has drawn the attention of designers and contractors as a fast pavement construction method. This type of pavement is placed and compacted with equipment similar to that of asphalt pavement and requires less time until traffic opening, compared to conventional concrete pavement. Technical advantages of this type of concrete over conventional concrete pavements are due to different rheological properties caused by aggregate grading type and mixture proportioning approach. The aggregate grading in this type of concrete contains a significant amount of fine aggregates and is in the aggregate grading range used for asphalt concrete [1]. Also, since RCC is mainly used for large-scale projects (e.g. dam and road construction), the dominant mixture proportioning approach usually seeks to minimize the cement paste's volume, and consequently,

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minimize the mixture manufacturing costs significantly. This type of aggregate grading and mixture proportioning will lead to mixtures totally different from conventional concrete mixtures, therefore, performing slump test to evaluate their workability is not possible (their slump is equal to zero). Thus, workability of RCC is measured utilizing the Vebe table and according to ASTM C1170 standard. In this method, the required time for a ring of mortar to be visible between the wall of the container and the surcharge on the vibrating mixture is used as the workability measurement criterion. RCC mixture proportions in the USACE mix design is also obtained according to the results of this test [2]. The main disadvantage of this method is the high dependency of the test results on the vibration parameters, due to the dependency of Bingham parameters of the concrete on the vibration parameters, in a way that the vibration velocity has the highest effect on the test results [3,4].

Considering this limitation, Paakkinen introduced a method for evaluating the fresh properties of stiff concrete mixtures by developing the Intensive Compaction Tester (ICT) device. Compaction of the specimens is performed without imposing any vibration or impact on this device, and an inclined piston compacts the mixture by applying pressure [5]. In recent decades, the ICT has been used for stiff concrete mixtures evaluation to a limited extent, and the device's output curves have been directly used as the comparison criteria for their fresh properties [6–8]. Moreover, the Superpave Gyratory Compactor (SGC) device, which was first developed to manufacture asphalt concrete specimens according to Superpave mix design methods, is used for dry manufacturing and evaluation of stiff concrete mixtures with a function similar to ICT. Nader Amer investigated the effects of the number of SGC gyrations on the density and mechanical properties of RCC mixtures and showed that increasing the number of gyrations leads to higher density and strength in specimens. They have also developed the linear model that relates the density and the tensile strength of mixtures in different water to cement ratios and suggested employing this model for mixture designs [9,10]. In addition, J. T. Kevern et al. defined the workability energy index (an index of mixture's density under the initial compaction energy) and compaction densification index (an index of the extra compaction energy required for the mixture to reach desired density) of the pervious concrete mixture as the area below the SGC output curve [11].

There are numerous studies in the literature evaluating the RCC, many of which aim at studying the feasibility of using supplementary cementitious materials and recycled aggregates in the mixtures [12–19]. Nonetheless, despite its significance, few studies have been devoted to optimizing the rheological properties of RCC. Conventionally, chemical admixtures are employed to manufacture RCCs with favorable rheological properties, the quantity of which is much greater than the quantity advised for conventional Concrete (PCC) due to low volume of cement paste in RCC mixtures [20]. Emulsion asphalt has also been used as an admixture for PCC and RCC in a few cases, which resulted in improvements in many properties, especially the durability properties of concrete [21–23].

The primary purpose of this research is to improve the fresh properties of concrete by utilizing Cationic Asphalt Emulsion (CAE). Therefore, the CAE was added to the mixture in 2%, 4%, 6%, 8% and 10% of the cement's mass, and Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) of the mixtures were obtained utilizing proctor mold and rammer. Workability and compactability of the mixtures were also investigated through SGC and were compared with the control mixture.

Compressive, flexural, and tensile strength tests were performed to evaluate the mechanical properties of the mixtures. Due to the importance of non-destructive tests, cubic specimens were subject to the ultrasonic test, in order to develop the compressive strength estimation model of the RCC containing CAE. Finally, ANOVA tests were conducted on the tests results at 5% significance level to investigate the effects of the variables on them.

2. Rheology of stiff concrete

Fresh concrete is a composite material containing particles with a dimension of 1 μm to 50 mm, in which the aggregates are suspended in the cement paste. The behavior of this material obeys the Bingham model, therefore, in order to evaluate its properties thoroughly and properly, yield stress (τ_0)and plastic viscosity (η) must be measured. Eq. (1). Illustrates the Bingham model and Fig. 1 shows the concrete mixture's behavior according to this model [24].

$$\tau = \tau_0 + \eta\dot{\gamma} \quad (1)$$

Higher roughness and fracture of the aggregates leads to higher interlock and friction angle in them, which results in a mixture with higher yield stress and plastic viscosity [25]. Another parameter that affects yield stress and plastic viscosity of the fresh concrete significantly is the level of adhesion among the aggregates. This adhesion has a different mechanism than that of the adhesion present among the soil particles (e.g. clay). There is no adhesion in the dry state of the aggregates and presence of moisture in the contact surface forms liquid bridges, which leads to capillary forces that themselves cause adhesion (Fig. 2) [26].

According to Eq. (2), the amount of force that causes the aggregates to adhere (assuming that they are spherical) depends on different parameters including liquid's surface tension (γ), aggregate's radius (a), half filling angle (ϕ), contact angle (θ) and pressure deficiency on the contact surface between the liquid and the air (Δp) [26].

$$\mathrm{F} = 2\pi\gamma \mathrm{a} \cdot \sin\phi \sin(\phi + \theta) + \pi \mathrm{a}^2 \Delta \mathrm{p} \cdot \sin^2\phi \quad (2)$$

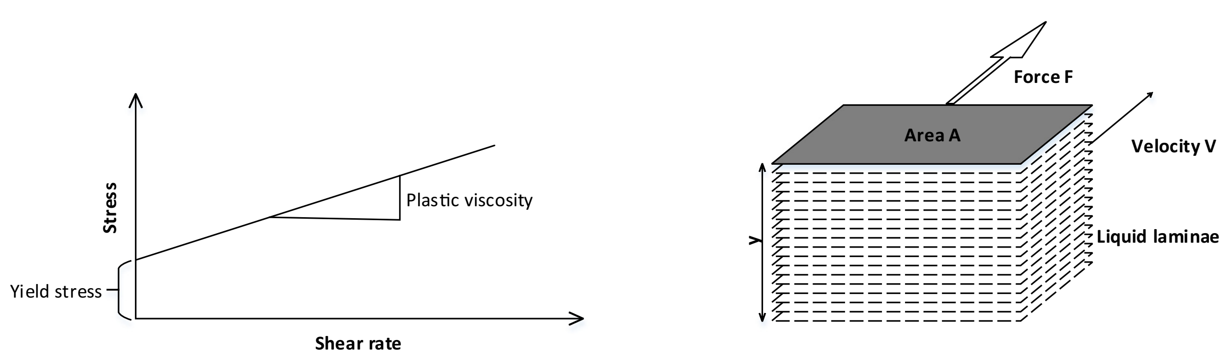

Fig. 1. Bingham model for describing the fresh concrete's behavior [24].

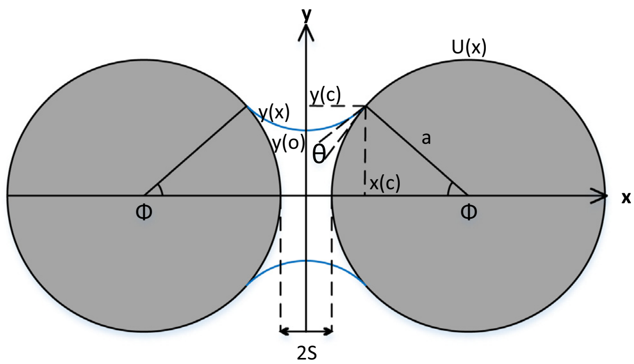

Fig. 2. Liquid bridge formation between 2 spherical non-adhesive particles, under the influence of moisture [26].

It can be seen that the liquid type and the aggregate's surface properties can influence the capillary force among particles by affecting the half-filling angle and the contact angle. Eq. (2) indicates that the amount of ϕ has more effects on the capillary force compared to θ. Also, θ is usually neglected due to its negligible effects and difficult measurement, so Eq. (2), is written in a new form, i.e. Eq. (3) [27].

$$F = 2\pi\gamma a \cdot \sin^2\phi + \pi a^2 \Delta p \cdot \sin^2\phi \qquad (3)$$

It can be inferred from Eq. (3) that reducing the amount of ϕ will significantly decrease the capillary force among particles. In this equation, if water is chosen as the liquid, the amount of ϕ will be influenced by hydrophilicity or hydrophobicity of the particles' surface, such that the hydrophobicity of the particles' surface reduces their connection surface with water, which consequently decreases the amount of ϕ and the capillary force [28].

3. Experimental program

3.1. Materials

Materials used for manufacturing concrete mixtures in this study include aggregates, cement, water and CAE. The aggregates utilized were fractured gravels that were obtained from the asphalt factory of Mashhad municipality. The requisite grading for the RCC was obtained by combining aggregates extracted from 3 different borrow pits, including 1 fine and 2 coarse aggregates. The grading of each borrow pit and the combination used are shown in Fig. 3. Physical properties of these materials were tested according to ASTM D2419, ASTM D5821, ASTM C127, ASTM C128, and, ASTM C136 and the results are presented in Table 1.

The cement used in the RCC is type 2 cement manufactured by Zaveh factory located in Torbat Heydarieh, Iran. Physical, chemical, and mechanical properties of this type of cement are presented in Table 2. In this research, CAE has been employed as an admixture for manufacturing RCC mixtures. Fresh rapid setting CAE with dark brown color that solid mass and density of which is respectively 60% and 1.01 g/cm^3 was obtained from Zarrin Oil Products Company.

3.2. Fresh properties

3.2.1. Optimum moisture and mixture proportions

In this research, a total number of 6 RCC mixtures were manufactured and tested, and the test result for mixtures containing 2%, 4%, 6%, 8% and 10% CAE were compared with results of the control mixture. Material proportions for each mixture were obtained by measuring the OMC according to modified proctor method. The amount of cement used in the mixtures was chosen to be 16% of the dry aggregates' mass by assuming the 28-day flexural strength equal to 5 MPa. In this method, the OMC is defined as the water content for which the specimen, compacted by the Modified Proctor Compaction Test, has the MDD. Each proctor specimen is manufactured in 5 layers and the compaction of each layer is done by 56 blows of a 44.48 N rammer dropping from a 457.2 mm height. To plot density-moisture curves, it is required to manufacture trial mixtures with different proportions of water. Therefore, for each CAE percentage, trial mixtures with 5%, 6%, 7%, 8% and 9% of water mass to aggregate mass ratio were manufactured (taking into account the amount of water present in the emulsion).

9 kg of dry aggregate with desired grading was prepared to manufacture each proctor specimen, and 1440 g of cement (16% of the aggregate's mass) was added thereto. After manufacturing

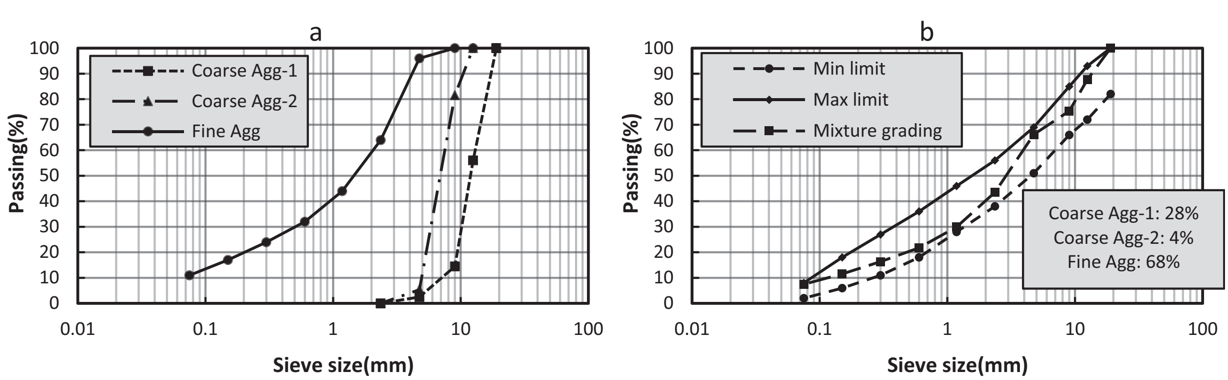

Fig. 3. Aggregates grading: (a) grading of fine and coarse aggregates (b) combined grading.

Table 1
Properties of the aggregates used for manufacturing the RCC.

Source	Specific gravity			Absorption (%)	Fractured particles (%)	Sand equivalent (%)
	Dry	SSD	Apparent			
Coarse Agg-1	2.645	2.681	2.743	1.35	95	–
Coarse Agg-2	2.601	2.652	2.741	1.97	95	–
Fine Agg	2.576	2.649	2.780	2.86	–	68

Table 2
Physical, mechanical and chemical properties of the cement.

Chemical properties Oxide (%)		Mechanical and physical properties Properties		
SiO_2	21.4	Compressive strength (MPa)	3 Day	19
Al_2O_3	4.95	–	7 Day	34
Fe_2O_3	3.91	–	28 Day	52.5
CaO	63.5	Specific gravity	–	3.02
MgO	2.6	Blaine specific surface (cm^2/g)	–	2900
Na_2O	0.4	Initial setting time (min)	–	90
K_2O	0.55	Final setting time (min)	–	170
SO_3	1.3	Autoclave expansion (%)	–	0.15
L.O.I (max)	0.9	–	–	–
I.R (max)	0.25	–	–	–

Table 3
Mixture proportions for each percent of the CAE in the RCC (kg/m^3).

Mix.	Cement	Cationic asphalt emulsion	Aggregate	Water	w/c
B0	308	0	1923	137	0.45
B2	307	6	1920	133	0.44
B4	306	12	1913	129	0.44
B6	306	18	1909	125	0.43
B8	306	24	1912	118	0.42
B10	306	31	1912	112	0.41

B_i : RCC mixture containing CAE by i% of cement mass.
w/c: This ratio has been calculated considering the water present in CAE.

3 proctor specimens for each moisture percentage and measuring the dry density for each specimen, moisture-density curves were plotted and their extreme points were chosen as the OMC. Mixture proportions were then obtained for each mixture according to Table 3, assuming a 2% air content and considering the density of the materials used.

3.2.2. Compactability and workability

In order to simulate field conditions and avoid impacting and vibrating the mixtures during the compaction, SGC device has been employed to evaluate fresh properties of the mixtures. In this device, the compaction is performed by two inclined gyrating pistons. This compaction method is very similar to the method used for dam and road pavement construction RCCs. Results of this test are affected by some parameters including the applied pressure, piston's inclination angle, compaction speed and maximum density limit. In this research, these values are assumed to be 200 KPa, 1.25Â°, 30 rounds/min and the theoretical density of the mixture, respectively. Fig. 4 shows the SGC device employed in this research.

The device measures the specimen's height after each gyration of the mold, and calculates its density and air content based on the specimen's mass and theoretical density. It also plots and saves the air and density curves through the compaction period, after the compaction is finished. Theoretical density of the mixtures is calculated according to relative amount of (P_i) and density (G_i) of each material used in concrete, assuming a 0% air content and according to Eq. (4). This density is introduced to the device before the operation starts.

$$G_m = \frac{P_C + P_A + P_W + P_{AE}}{\frac{P_C}{G_C} + \frac{P_A}{G_A} + \frac{P_W}{G_W} + \frac{P_{AE}}{G_{AE}}} \quad (4)$$

Fresh concrete's density curve is then plotted against gyrations according to the SGC device's output, after the compaction is finished. To calculate the Workability Energy Index (WEI) and Compaction Densification Index (CDI) of the pervious concrete according to [11], the mixture's density is plotted against gyration

Fig. 4. The Superpave Gyratory Compactor device used for the mixture compaction purpose.

number, as a percentage of the theoretical density. The area below the curve is then calculated as shown in Fig. 5. WEI indicated the level of compaction of the pervious concrete under the initial compaction energy, while CDI is the amount of extra compaction energy required for the pervious concrete to reach the favorable density.

In this study, The RCC used for pavement purpose has been studied, therefore, the area below the curve is calculated until the mixture has reached the desired field density so that the obtained CDI is an indicator of the amount of extra compaction energy required to reach the desired field density. Accordingly,

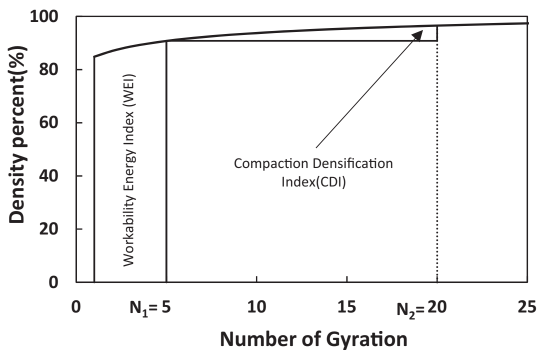

Fig. 5. WEI and CDI calculation method for the pervious concrete based on J.T. Kevern et al. [11].

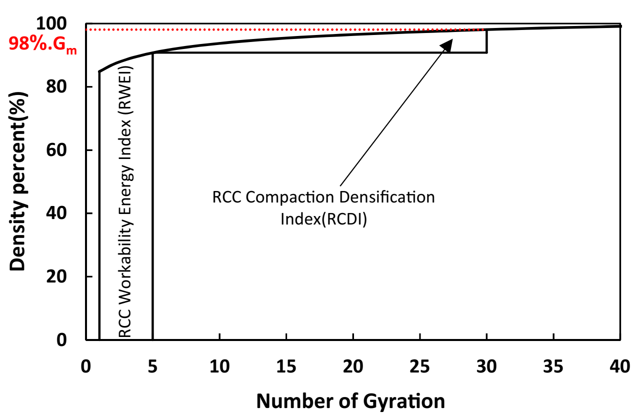

Fig. 6. RWEI and RCDI calculation method regarding the area below the density percentage curve.

N_2 was considered to be the number of gyrations required for the mixture to reach 98% of its theoretical density, thus, RCC Workability Energy Index (RWEI) and RCC Compaction Densification Index (RCDI) were calculated according to Fig. 6. Each mixture requires a specific amount of energy to reach the favorable density based on its fresh properties; thus, improving the fresh properties leads to a decrease in the N_2. This is why the method adopted to calculate RCDI in this research aims at normalizing the mixtures according to the number of gyrations against the earlier method.

3.3. Mechanical properties

3.3.1. Casting and curing method

A challenge that the research on RCC usually face is the molding of test specimens with different shapes, due to high stiffness of RCC mixtures. Current standards in this area suggest employing the vibrating table (ASTM C1176) and the vibrating hammer (ASTM C1435). Unfortunately, the standard methods mentioned above can only be used to mold cylindrical specimens. It should be mentioned that a standard for molding the RCC mixtures in rectangular molds using the vibrating hammer is currently being developed (ASTM WK41101).

In this research, a vibrating hammer equipped with special replaceable plates was used for molding the mixtures. Cylindrical specimens were molded in 4 lifts and according to the standard while cubic and beam specimens were molded in 3 lifts due to their lower heights. These specimens were demolded after a day and were cured by immersing until the test date.

3.3.2. Test method

Mechanical properties are cited as the most common concrete quality evaluation criteria in many manuals, and dimensions of different concrete structures are designed according to these properties. Therefore, there's a special emphasis on mechanical properties of the mixtures in this research, and compressive, tensile and flexural strength tests were performed on the mixtures. To evaluate each of these properties, 4 specimens were tested in 7, 28 and 90 days of age. According to BS EN 12390-3:2002 standard, 4 cubic specimens with 100 × 100 × 100 mm dimensions were tested in 7, 28 and 90 days of age, to measure the compressive strength. According to the standard's recommendation, the loading rate was chosen to be 3 kN/s (or 0.3 MPa/s). Available standards on flexural strength measurement suggest 2 different methods including center-point loading (ASTM C293) and the third-point loading (ASTM C78), of which this research has adopted the ASTM C78 method and performed the test accordingly. A 100 × 100 × 400 mm dimension was selected for beam specimens and the load was applied with a 0.055 kN/srate (equal to a 1 MPa/min increase in the maximum stress of the tension face) in a 150 mm distance from both ends of the beams. Similar to the compressive strength test, 4 specimens were tested in 7, 28 and 90 days of age. To measure the tensile strength of the mixtures in 7, 28 and 90 days of age, 4 cylindrical specimens each having a standard 100 × 200 mm dimension were tested for each mixture according to ASTM C496. In this test, the loading rate was also chosen to be 0.052 kN/s (equal to a 1 MPa/min increase in the stress of the loaded plane).

3.4. Ultrasonic pulse velocity (UPV) test

One of the non-destructive tests performed on the concrete is the UPV test, which is frequently used for evaluating the concrete's quality, especially the mechanical properties of the concrete, due to its high speed and repeatable results. Therefore, this test was performed on cubic specimens before fracturing them in the compressive strength test, and the results were presented in the form of strength estimation models. The test was performed according to ASTM C597 standard, using the Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT) device. The utilized device is equipped with two transducers with 50 mm diameters, which create pulses with 54 kHz frequency in the specimen. The passing time of these pulses through the specimen is measured with a 0.1 μs precision by the device.

4. Results and discussion

4.1. Fresh properties of concrete

4.1.1. Optimum moisture and maximum density

Dry mass of the proctor specimens was measured after compacting and drying them in the 110 °C oven for 24 h, and the moisture-density curves were plotted for each mixture (Fig. 7). As it can be seen, there were two major changes in the moisture-density curves, i.e. a reduction in the OMC and an increase in the MDD. Quantities of the OMC and the MDD are presented in Table 4, for each mixture.

The moisture-density curve for the RCC follows a quadratic equation and comprises of an ascending and a descending end. The ascending end of the curves indicates mixtures which contain cement paste in a lower volume than the voids among compacted aggregates. Filling these voids with the cement paste will lead to an increase in the mixture's density in this end of the curve. Besides this reason, the other factor that increases the density of the mixture in this end of the curve is the decreased friction among

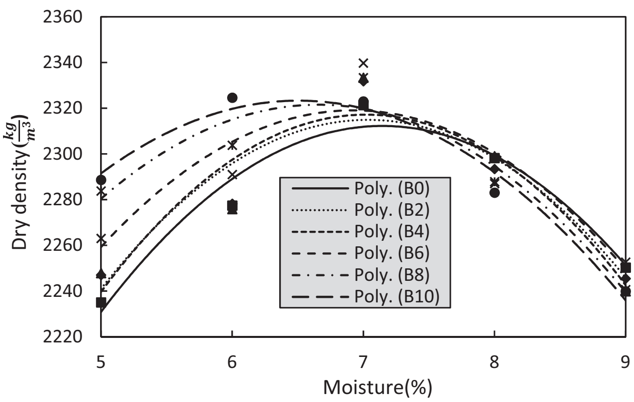

Fig. 7. Moisture-density curve for mixtures containing different amounts of CAE.

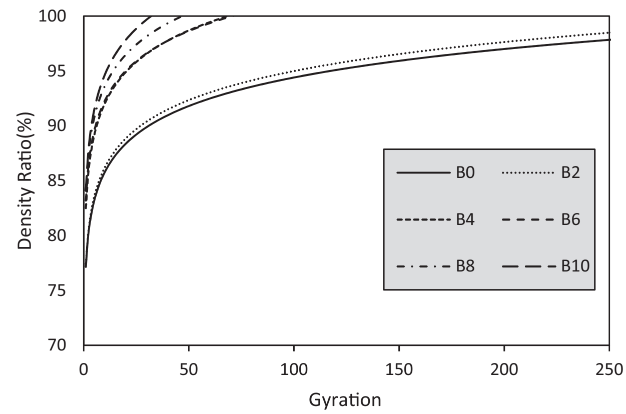

Fig. 8. Mixtures' density ratio during the compaction in SGC.

aggregates due to the increased amount of cement paste which facilitates their movement. The reduced percentage of the OMC for mixtures containing CAE is also caused by the decreased friction among aggregates since the amount of aggregates and their grading is similar among all mixtures, and therefore, the voids among aggregates are also similar, leading to identical amounts of the required cement paste to fill these voids for all mixtures. Thus, the reduction in the OMC of mixtures containing CAE is due to the decreased friction among aggregates. However, the presence of the CAE as a lubricant facilitates the movement of the aggregates and decreases the amount of voids, resulting in a decrease in OMC and a slight increase in the density.

The descending end of the curve indicates that the volume of the cement paste is more than the voids among aggregates. In this end of the curve, increasing the moisture will increase the water's share in the mixture's total volume, and the aggregate and cement's share in the total volume decreases, which leads to a decrease in the mixture's density. Therefore, the volume of water has the highest effect on the mixture's density, and, the friction among aggregates does not have a significant effect on mixtures' density since the voids among aggregates are completely filled. Adding CAE to the mixture has an effect similar to that of adding water, since water and CAE have similar densities, therefore, increasing the CAE content leads to a reduction in cement and aggregate's share in the mixture's total volume in the descending end of the curves, and causes a drop in the density. This drop is marginal since a small amount of CAE has been used.

4.1.2. Workability and compactability indices

Each mixture was compacted by the SGC device and the height of specimens was obtained as the device's output throughout the test. After each gyration, the specimen's density was calculated, considering its mass and the mold's cross section. The *density/theoretical density* ratios were then obtained in percentages and were plotted against gyration number. Fig. 8 illustrates the curve of the mixtures' density ratio model, which was developed considering the average of 3 test outputs for each mixture.

It can be seen that increasing the CAE content will generally move the density curve upwards, however, significant transformations and displacements occur in curves when the amount of CAE is increased to more than 2%, which dramatically increases the area below the curve. Table 5, shows the amount of RWEI, RCDI, air void (in N_2) and the density ratio (in N_1) for each mixture.

As it is shown in Table 5 and Fig. 9, increasing the amount of CAE causes the RWEI to increase and a reduction in the RCDI. Thus, presence of CAE has resulted in higher mixture densities under initial compaction and less required energy to reach the favorable density. Workability and compactability of mixtures is highly dependent on the inter-aggregate forces in the mixture.

As it was mentioned in Section 2, in fresh RCC, due to high dryness and low amounts of cement paste, adhesion among aggregates is caused by capillary forces and liquid bridges. Since asphalt is hydrophobic, formation of a thin asphalt layer around aggregates directly reduces capillary forces. Presence of a hydrophobic asphalt layer on the surface of aggregates reduces the contact surface of liquid bridges with them and therefore decreases the value of ϕ.

Table 5
Mixture compaction curves' results.

Mix	RWEI	RCDI	N_1 = 5	Air Void = 2%
			Density percent (%)	N_2
B0	324	2751	83.1	248
B2	325	2101	83.6	196
B4	347	186	89	39
B6	349	189	89.5	39
B8	353	114	90.7	28
B10	355	55	91.4	19

Table 4
Characteristics of moisture-density curves of mixtures.

Mix	Dry density model	R^2	OMC (%)	MDD (kg/m^3)
B0	$\rho_d = -17.694\omega^2 + 252.8\omega + 1409$	0.95	7.1	2312
B2	$\rho_d = -17.865\omega^2 + 251.3\omega + 1431$	0.87	7.0	2315
B4	$\rho_d = -19.007\omega^2 + 266.8\omega + 1381$	0.86	7.0	2317
B6	$\rho_d = -16.153\omega^2 + 223.7\omega + 1545$	0.82	6.9	2319
B8	$\rho_d = -14.954\omega^2 + 199.1\omega + 1659$	0.92	6.7	2322
B10	$\rho_d = -15.226\omega^2 + 197.6\omega + 1684$	0.97	6.5	2325

OMC: Optimum Moisture Content.
MDD: Maximum Dry Density.

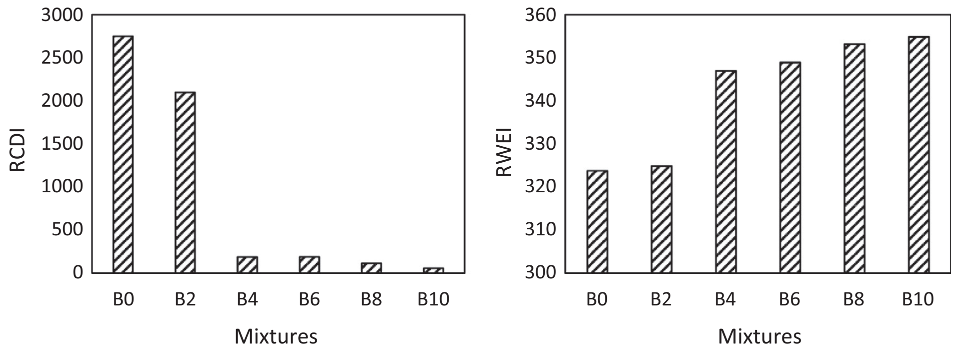

Fig. 9. RWEI and RCDI of mixtures containing different amounts of CAE.

On the other hand, regarding Eq. (3), capillary force corresponds with $\sin^2\phi$, thus, a reduction in ϕ can cause capillary force to dramatically drop and reduces aggregate adhesion as a result. Different liquid bridges in ordinary aggregates and aggregates covered with asphalt are schematically shown in Fig. 10.

Internal friction is another force present among aggregates which affects mixtures' rheological properties, and is dependent on the level of fracture and roughness of aggregates [29]. Covering the surface of aggregates reduces their roughness, and as a result, decreases the friction angle. Significant improvements in workability of mixtures containing more than 2% CAE can be caused by great reductions in surface roughness of aggregates due to the presence of asphalt. As it is shown in Fig. 11, the amount of CAE in mixture B2 is enough to form a very thin layer of asphalt on the surface of aggregates, which is not thick enough to eliminate the roughness on the surface and form a smoother surface. However, increasing the amount of CAE to 4% will make the asphalt layer thick enough to significantly reduce the roughness and form a smoother surface.

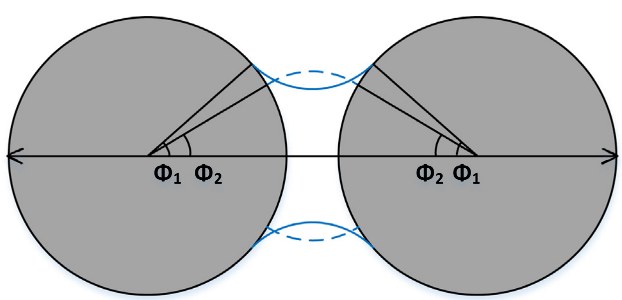

Fig. 10. Half-filling angles for ordinary aggregates (ϕ_1) and asphalt covered aggregates (ϕ_2).

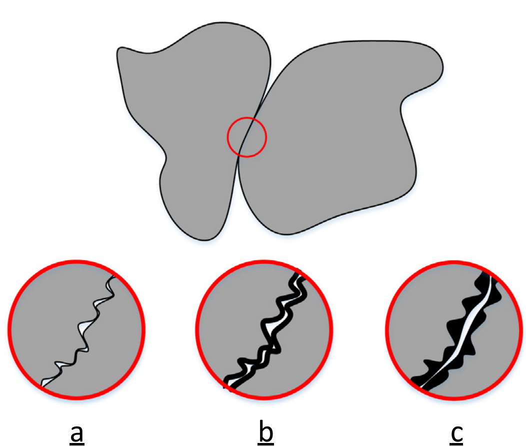

Fig. 11. A comparison between aggregates' connection surface (a) Ordinary aggregate (b) B2 mixture (c) B4–B10 mixtures.

4.1.3. Analysis of variance on fresh concrete's properties

In order to investigate the significance of the effects of employing CAE as an admixture on fresh properties of mixtures, one-way analysis of variance (ANOVA) was performed on test results considering the CAE content as the source of variance. In addition to RWEI and RCDI, dry density of specimens containing 7% of water was also analyzed to investigate the effect of CAE on them. The trial mixtures with 7% water was chosen since it has the moisture that is closest to the OMC of mixtures. Table 6, shows results of the ANOVA at 95% confidence level. In order to compare the properties of fresh mixtures containing CAE with the control mixture and to evaluate the relevant significant difference with the control mixture, Dunnett's comparison method was applied to the mixtures' results. In this method, the significant difference of the properties for each mixture is compared to the control mixture and the p-value for each mixture is calculated. It can be seen that although CAE has a significant effect on RWEI and RCDI, the dry density of proctor specimens was not significantly affected by it. It seems that this difference is caused by different compaction energies among specimens manufactured by SGC and modified proctor. Table 7 illustrates compaction energy of SGC and proctor specimens.

It can be seen on Table 7 that the amount of energy applied on the specimen in the modified Proctor method is so much higher than the compaction energy in SGC method. The high amount of compaction energy applied on the mixture in this method can completely overcome internal friction and capillary forces, thus, compacts the mixture to the highest possible level. Results of the Proctor test are, therefore, only affected by the amount of cement paste in the mixtures. Conversely, these 2 forces are the most affected by the presence of CAE, and the cement paste volume has only been marginally increased.

4.2. Mechanical properties

4.2.1. Results of the mechanical tests

Figs. 12–14 indicate the results of the mechanical tests performed on the mixtures at different ages. It can be seen that increasing the amount of CAE caused the mixture's strength to decrease. This reduction can be caused by two reasons; firstly, the cement particles are covered by the asphalt and therefore are not completely hydrated, and secondly, the covered surface of the aggregates made their adhesion to the cement paste weaker, and consequently, the concrete ruptures under lower stresses.

In addition, it can be seen that increasing the curing age of the mixtures have improved their strength. This strength is the result of development in the hydration and further production of this reaction's hard products (C-S-H).

Table 6
ANOVA results for fresh mixtures' properties.

Source of tests	Difference of levels (Dunnett comparison)	Difference of means	SE of difference	95% CI	T-value	Adj P-value
Fresh properties						
RWEI	B2 – B0	1.12	4.65	(−12.37 ; 14.60)	0.24	0.999
	B4 – B0	23.23	4.65	(9.75 ; 36.72)	5.00	0.001
	B6 – B0	25.18	4.65	(11.70 ; 38.67)	5.42	0.001
	B8 – B0	29.48	4.65	(16.00 ; 42.97)	6.34	0.000
	B10 – B0	31.12	4.65	(17.64 ; 44.61)	6.70	0.000
RCDI	B2 – B0	−650.2	92.6	(−918.9; −381.6)	−7.02	0.000
	B4 – B0	−2564.9	92.6	(−2833.5; −2296.3)	−27.70	0.000
	B6 – B0	−2562.6	92.6	(−2831.2; −2294.0)	−27.68	0.000
	B8 – B0	−2637.8	92.6	(−2906.5; −2369.2)	−28.49	0.000
	B10 – B0	−2696.4	92.6	(−2965.0; −2427.8)	−29.12	0.000
Dry density (7%)	B2 – B0	10.4	26.3	(−65.9; 86.7)	0.40	0.993
	B4 – B0	12.0	26.3	(−64.3; 88.3)	0.46	0.987
	B6 – B0	18.4	26.3	(−57.9; 94.7)	0.70	0.927
	B8 – B0	12.0	26.3	(−64.3; 88.3)	0.46	0.987
	B10 – B0	1.6	26.3	(−74.7; 77.9)	0.06	1.000

Table 7
Compaction energy of specimens manufactured by SGC and modified Proctor.

Mixture	SGC compaction energy (kN.m/m^3)	Proctor compaction energy (kN.m/m^3)
B0	48.0	2700
B2	46.9	2700
B4	32.4	2700
B6	31.3	2700
B8	29.8	2700
B10	30.2	2700

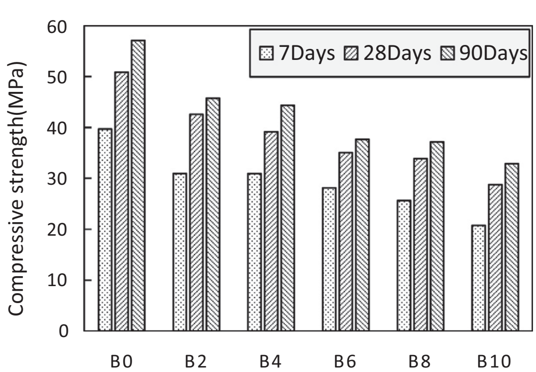

Fig. 12. Results of the compressive strength test.

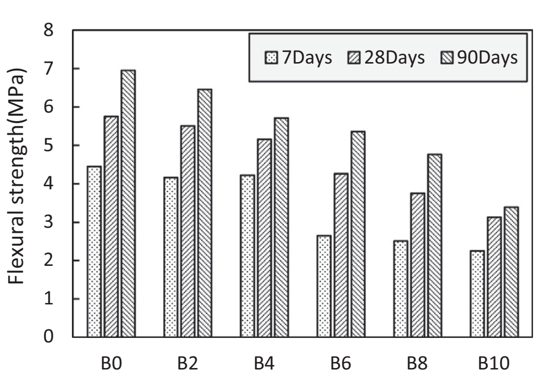

Fig. 13. Results of the flexural strength test.

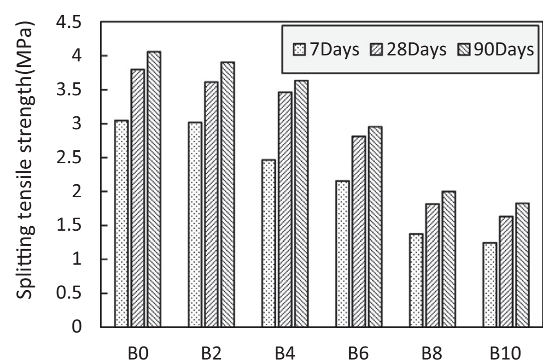

Fig. 14. Results of the tensile strength test.

4.2.2. Analysis of variance of the mechanical properties

In this research, effects of the age and CAE content variables on the mechanical properties of the mixtures have been investigated. Therefore, to evaluate the significance of the difference among the mechanical properties of the mixtures, a two-way ANOVA was conducted on the test results at 5% significance level. Results of the ANOVA are presented in Table 8. It can be seen that increasing the CAE content and the curing age of the mixture have resulted in a significant decrease and increase in the mechanical properties, respectively. Also, interactions between the age and the CAE con-

Table 8
Results of the ANOVA test on the mechanical properties of the mixtures.

	Source	Adj SS	DF	Adj MS	F-Value	P-Value
Compressive strength	CAE	3397.1	5	679.4	77.9	0.000
	Age	2174.1	2	1087.1	124.6	0.000
	CAE*Age	86.6	10	8.7	1.0	0.462
	Error	471.2	54	8.7		
	Total	6129.0	71			
Tensile strength	CAE	48.7	5	9.7	127.6	0.000
	Age	9.4	2	4.7	61.4	0.000
	CAE*Age	0.7	10	0.1	1.0	0.477
	Error	4.1	54	0.1		
	Total	62.9	71			
Flexural strength	CAE	71.4	5	14.3	35.6	0.000
	Age	52.7	2	26.3	65.5	0.000
	CAE*Age	4.3	10	0.4	1.1	0.403
	Error	21.7	54	0.4		
	Total	150.1	71			

tent did not have a significant effect on the mechanical properties. In other words, the effect of the CAE content on the mechanical properties of concrete does not depend on the mixture's age.

4.3. Ultrasonic pulse velocity

To develop the compressive strength estimation model for each mixture, UPV was measured in each cubic specimen before the compressive strength test. Fig. 15 shows the ultrasonic test results at different ages. It can be seen that increasing the CAE content has decreased the UPV in the mixtures, which is caused by mixtures' decreased stiffness.

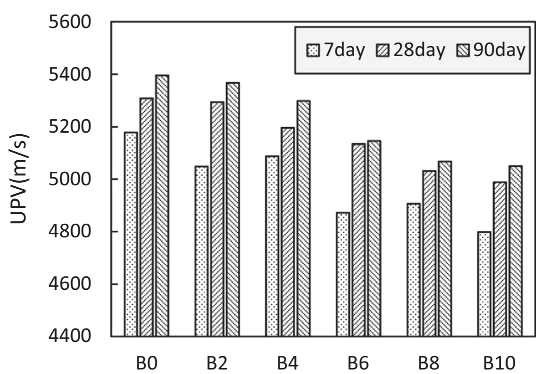

Fig. 15. UPV in mixtures containing different amounts of CAE, at different ages.

The presence of CAE can result in decreased mixtures' stiffness in two ways; firstly, the mixture's stiffness decreases due to the relatively lower stiffness of asphalt compared with other materials in the concrete, and secondly, lower production of the hydration's products due to incomplete hydration of the cement particles has caused a drop in the mixture's stiffness. Fig. 16 shows the models derived from this evaluation.

4.4. SEM images

To evaluate the effects of asphalt on the microstructure of the mixtures, proper pieces for preparing the SEM images were obtained by cutting the fracture section of the cylindrical specimens. Surface of the aggregates and cement paste in mixtures B0 and B8 were compared with each other according to Fig. 17 which shows SEM images with a 500× magnification. The asphalt cover, which can be seen in mixture B8, leads the micro-cracks' path around aggregates by weakening the adhesion among aggregates and cement paste and therefore causes the specimen to fracture.

Fig. 18, which illustrates the micro-structure of the mixtures, was obtained from mixtures B0 and B4 with a 10,000× magnification. The thin layer of asphalt which prevents enough water to reach cement particles and thus stop their complete hydration, can also be seen in this image.

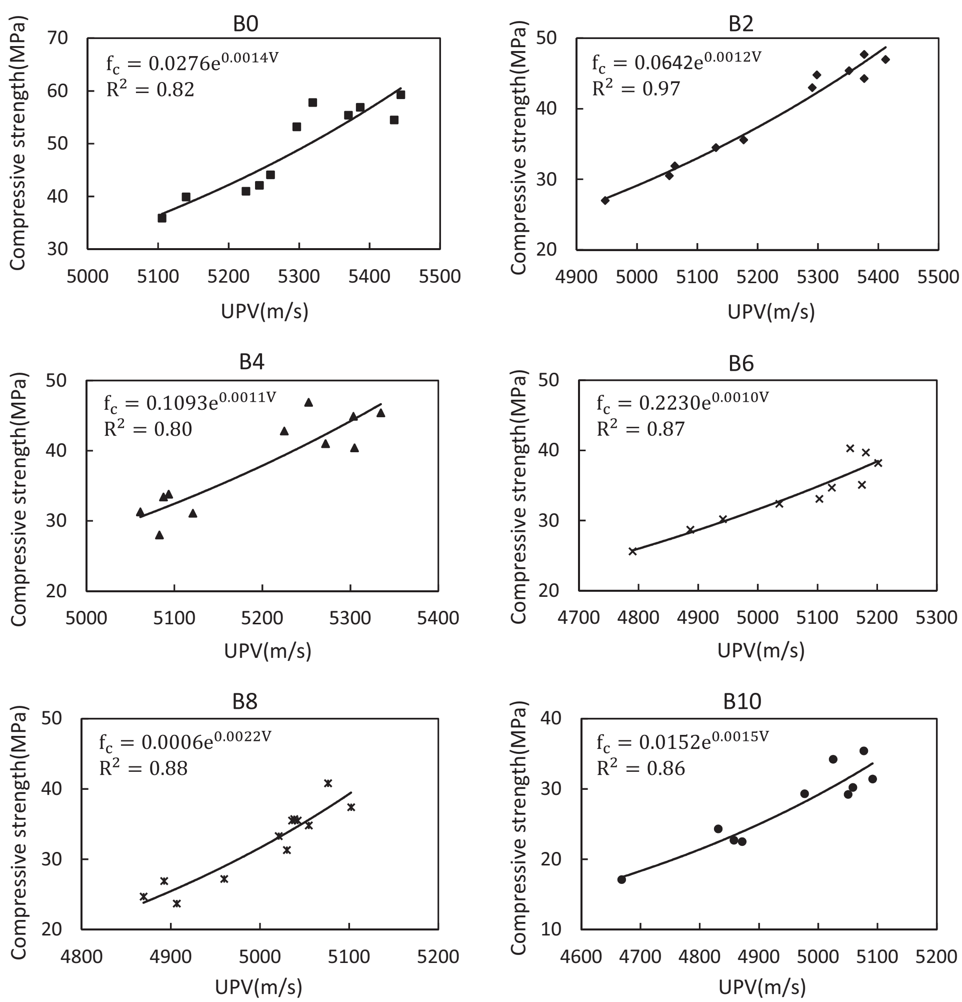

Fig. 16. Compressive strength estimation models using ultrasonic test.

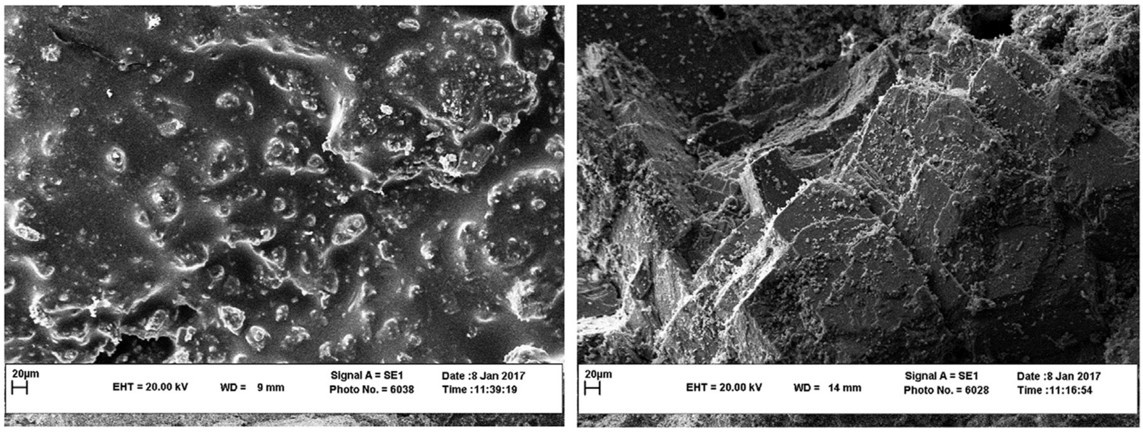

Fig. 17. SEM image of mixtures B0 (right) and B8 (left) with a 500× magnification.

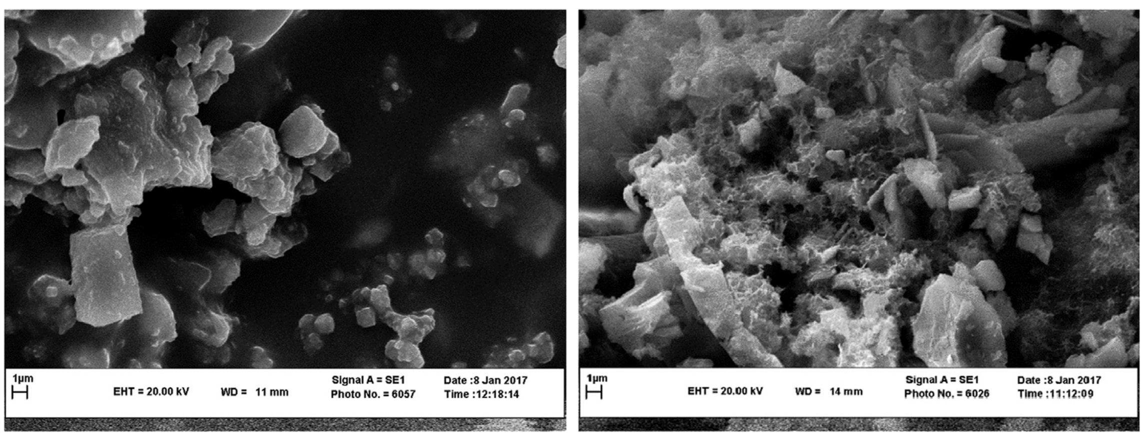

Fig. 18. SEM image of mixtures B0 (right) and B4 (left) with a 10,000× magnification.

5. Conclusions

The purpose of this study is to evaluate fresh and mechanical properties of the RCC mixtures containing CAE as an admixture. To this end, CAE was added to the mixtures in percentages ranging from 2% to 10% and their fresh properties were investigated by manufacturing Proctor and SGC specimens. In addition, mechanical properties of the mixtures were measured and compared by performing compressive, tensile, and flexural strength tests on cylindrical, cubic, and beam specimens. Test results generally suggest that the fresh properties of the mixtures are improved while their mechanical properties are dropped. Conclusions and recommendations derived from this study can be summarized as follows:

- Increasing the RWEI and decreasing the RCDI show a decrease in the required compaction energy to reach the desired density in the RCC mixtures when increasing their CAE content. This effect can result in faster construction and lower costs in the field by decreasing the number of required roller passes to reach the desired density.
- Comparisons between Proctor and SGC specimens show a high compaction energy for proctor specimens which makes the results of this test insensitive to changes in fresh properties of the mixtures. Therefore, if the purpose of this test is to evaluate the workability and compactability of the mixtures, it is recommended that the amount of compaction energy is reduced in a way that makes its results coordinated to that of more precise tests (e.g. SGC and ICT).
- Since the results of the SGC device are too sensitive to even slightest changes in the fresh properties of the mixtures, its employment for evaluation of RCCs and other materials with similar field compaction methods (e.g. soil) is recommended.
- Although utilizing CAE has led to improved fresh properties of the mixtures, supplying minimum design strength must also be taken into consideration. Therefore, a tradeoff must be made between the decreased execution costs due to higher workability and the increased costs due to the extra cementitious materials consumption; the CAE should be used if there is an economic justification.
- It can be seen that employing the CAE as an admixture has led to a drop in all mechanical properties. The maximum strength drop in comparison to the control mixture, has occurred in the splitting tensile strength test of the B10 mixture which reached 59% in 7 days of age. Therefore, the decreased adhesion between the cement paste and the aggregates covered with asphalt can be interpreted as the main reason for the drop-in strength (especially the tensile strength).
- Regarding the fact that applying 4% of CAE had a significant effect on workability of the mixtures and using higher amounts did not make any significant improvements in workability, and considering the improvement in durability factors in mixtures containing this amount of asphalt emulsion [21–23], applying 4% of CAE is recommended in manufacturing RCC mixtures to avoid drops in the mechanical properties as well.

Conflict of interest

There is no conflict of interest.

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Future research

It is suggested that, in cases where there is a loss of strength due to significant content of CAE in mixtures, pozzolan materials such as silica fume, nano-silica and fly ash should be used to compensate such loss.

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