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Effect of cationic asphalt emulsion as an admixture on transport properties of roller-compacted concrete

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HIGHLIGHTS

- Cationic asphalt emulsion(CAE) was used as an admixture in RCC.
- Transport properties of CAE-containing RCC were investigated.
- ANOVA and intrinsically linear regression were used to evaluate results of tests.
- The SEM images were employed to interpret the results.
- If CAE is added equal to 4% or more, transport properties would be improved.

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ABSTRACT

This study aims to investigate the effect of cationic asphalt emulsion (CAE) as an admixture on durability characteristics of roller compacted concrete (RCC). To this aim, the CAE was added to the RCC mixture at 0%, 2%, 4%, 6%, 8%, and 10% of the cement mass; these mixtures were designed by the maximum density method according to ASTM D1557. The cubic and cylindrical specimens were fabricated using vibrating hammer; water absorption, sorptivity, water penetration depth, and electrical resistivity tests were conducted to evaluate the durability of the mixtures. The water penetration test was carried out on cubic specimens in accordance with BS EN 12,390-8: 2009; moreover, by cutting each cylindrical specimen, two 100 × 50 mm discs for conducting sorptivity and one 100 × 100 mm cylinder for conducting the water absorption and electrical resistivity tests were prepared. The results indicated that the decrease in the water absorption, penetration and sorptivity, and the increase in the electrical resistivity of the mixtures can be obtained by increasing the CAE content. Also, the analysis of variance (ANOVA) at 95% confidence level based on Dunnett comparison procedure denoted a significant improvement in the RCC transport properties by adding CAE. Scanning electron microscope (SEM) images were studied and it was revealed that filling the capillary pores and coating the inner surface of larger pores with asphalt exhibited a change in the structure of cement paste pores and demonstrated an improvement in the transport properties of the RCC. Performing electrical resistivity test is of great importance for evaluating the durability of concrete due to its non-destructive and rapid properties. Therefore, intrinsically linear regression models were estimated between its results and other durability indicators, which show proper fits based on their coefficient of determination (minR^2 > 0.83). The findings revealed that electrical resistivity test can be employed to estimate the various transport properties of the RCC.

1. Introduction

Roller compacted concrete (RCC) is defined as a type of concrete that, in its unhardened state, is able to support a roller while being compacted. The amount of cement paste required in this concrete is just as much as filling the voids between the aggregates and the water content is designed for having enough workability [1]. The first implementation of roller-compacted concrete pavement (RCCP) dates back to 1930 in Sweden [2]. In North America, the first experience with the construction of RCCP occurred in 1942 during the construction of an airport runway in Washington. However, in Canada, the RCC was first used as a surface layer in 1976 in the construction of a log sorting yard. The initial design was a layer of stabilized aggregates with a thickness of 14 in. as the base layer

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and 2 in. of asphalt concrete surface. However, a pavement with a thickness of 14 in. consisting of an 8 in. stabilized base with 8% cement and 6 in. aggregates with 13% cement was built upon the request of the owners. This positive experience in the construction of RCCP increased the application of this type of pavement in Canada in the following years.

The main difference between the RCC and conventional concrete is the amount and gradation of the aggregates, amount of cement, and water; so that the aggregates used in the construction of the RCC are dense- or well-graded and make up 75% to 85% of the total volume of the materials. Also, the amount of fine aggregates is higher than those of conventional concrete. These factors cause high stiffness of the fresh RCC and zero (or less) value of the slump, so that it cannot be compacted using traditional concrete paving machines [3]. Due to the large surface of RCCP and its potential exposure to a variety of harsh conditions (e.g. freeze–thaw cycles), durability of this type of concrete and its proper performance under these conditions is very important. Although concrete is damaged due to various factors, water transport properties have a direct influence on concrete durability against non-mechanical damages [4,5]. Water transport in concrete is carried out by various mechanisms, including diffusion (displacement of mass or ion due to concentration difference), sorption (water displacement due to capillary action), permeability (movement of water under pressure), migration (displacement of ions due to force of electrical field) and adsorption (fixation of water molecules on the surface of materials) as the main cases among others [6–10]. The surface contact of unsaturated concrete with water leads to the absorption of moisture due to the porosity of concrete and its capillary action. This is the most important measurable property in porous solids and can be used as a suitable indicator for the evaluation of various building materials, considering the ease of testing and the reproducibility of its results [11]. The penetration depth of water under the pressure in concrete is one of the most notable properties. Low permeability of concrete can result in its durability against a variety of destructive conditions, including freezing and thawing, aggressive chemical exposure, carbonation, sulfate and chloride attack [12]. Water transport properties of concrete are directly dependent on the volume and connectivity of the pores, and these values affect the permeability and diffusion. Permeability is caused by the flow of water due to the difference in pressure, while diffusion occurs as ion flow due to the difference in concentration. Therefore, it is possible to measure the electrical resistivity by applying a voltage to the saturated concrete and creating an electric current, which can be employed as an indicator of the concrete transport properties [13].

Although some studies have been conducted on the evaluation of water transport properties in the RCC, there is a necessity of more attention in this area. For example, Karimpour examined the effect of using a ground granulated blast furnace slag (GGBFS) on the optimal time span between mixing and compacting and considered concrete transport properties as a criterion for choosing this time span. This study showed that, in the case of increasing the time interval between mixing and compacting, replacement of cement by GGBFS can improve the RCC's transport properties [14]. Hazaree et al. investigated the capillary water transport characteristics of RCC and their association with freeze-thaw durability. In this study, various variables including cement content, water to cement ratio, curing time and surface finishing were considered and a wide range of capillary transport values were obtained. The results of this study showed that sorptivity of RCC was comparable to conventional concrete and decreased with increasing cement content as well as decreasing water to cement ratio. Furthermore, the results of the freeze-thaw durability test had a satisfactory correlation with sorptivity, so that the increase in the amount of capillary absorption reduced the durability [15]. Yerramala and Babu examined the transport properties of high volume fly ash RCC with cement content of 50 to 260 kg/m3, consisting of 40% to 85% of the fly ash. Permeability, water absorption, sorptivity, and chloride diffusion tests showed that mixtures containing moderate cement and fly ash had a better performance in terms of transport properties [16]. Mardani-Aghabaglou et al. evaluated the high-volume fly ash RCC mixtures with two alternative approaches of replacement of either cement or aggregate with fly ash. The mixture proportions obtained from the maximum density method included a water to cement ratio of 0.39 to 0.47. The results indicated improvement of transport properties as well as freeze–thaw resistance of the mixtures in the case of replacing aggregate by fly ash and inversely in the case of replacing cement by the fly ash [17]. Recently, studies have also been carried out to evaluate the use of trass as a natural pozzolan. For example, Ghahari et al. concluded that the use of a trass as a pozzolan in RCC mixture could improve its transport properties [18]. Ramezanianpour et al. reported a negative effect on the use of trass as a cement material on transport properties of RCC and showed that this pozzolan material increases permeability and capillary absorption of the mixture [19].

A number of studies have been conducted on the use of the asphalt for concrete construction to improve its properties. Kosior-Kazberuk and Jezierski demonstrated that the addition of cutback asphalt up to 13% of cement weight could significantly improve the scaling resistance of the mixtures [20]. Bołtryk et al. reported improvement of the durability and transport properties of concrete mixture containing 5% and 10% asphalt dissolved in organic solvent, and ascribed the improvement of properties to the hydrophobic property of asphalt and improvement of the pores structure of concrete as the major causes [21]. Bołtryk and Małaszkiewicz investigated the effect of using anionic asphalt emulsion as 2% and 4% on concrete properties. The results of this study showed a decrease in compressive strength of the mixtures and improvement of their microstructural properties, reducing the dimensions of concrete pores and improving its durability. An examination of scanning electron microscopy (SEM) images shows the fibrous structure of asphalt in a hardened cement paste. The reason for the improvement of transport properties and durability of mixtures is the presence of hydrophobic and insulating layer on the wall of cement paste pores [22]. In the course of their work, Bołtryk et al. began to build the concrete surface layer of multimodal reload terminal in the duty-free zone in Małaszewicze, Poland. In order to reduce the water absorption and increase the resistance of concrete against corrosive environmental conditions, anionic asphalt emulsion was used as an admixture in the concrete mixture. The superplasticizer was also employed to achieve the desired mechanical performance. The results of the study indicate a decrease in water absorption of the mixture and improvement of the frost resistance. In this research, the implementation of concrete pavement containing anionic emulsion asphalt was successfully tested, which revealed a high bearing capacity in corrosive environments [23].

Due to the fact that road pavement is exposed to a variety of destructive conditions as well as the use of various aggregates to produce RCC mixtures during construction of the project, its durability is of particular importance. In this research, cationic asphalt emulsion (CAE) was used in constructing RCC as an admixture to improve the transport properties since they control the durability of the mixture and their improvement can guarantee mixture performance under harsh conditions. A rapid-setting CAE has been selected due to its high production and reasonable prices in Iran.

According to the studies carried out so far by Huang et al., it is observed that the presence of asphalt in concrete can have a negative effect on its mechanical properties [24,25]. Therefore, the mechanical properties of the mixtures were also evaluated and would be revealed in another paper in order to present a detailed explanation and assessment of the results.

2. Experimental program

2.1. Materials

Materials used for the concrete construction include aggregates, cement, water and CAE. Cement Type 2 based on ASTM C150 was used. It is manufactured by Zaveh Torbat Cement Factory, the properties of which are given in the Table 1. The crushed coarse and fine aggregates were obtained from the asphalt factory of Mashhad municipality. Fig. 1 shows the gradation of the aggregates used in the construction of RCC, obtained from a composition of 68% fine and 32% coarse aggregates. Cationic rapid-setting asphalt emulsion was provided by Zarin Asphalt Technology Company with specifications reported in Table 2.

2.2. Mixture proportion

In this study, the CAE was added to the RCC by 0%, 2%, 4%, 6%, 8%, and 10% of cement mass (each percentage includes water and residual binder of the CAE). The cement content was 16% of the mass of aggregates, which is equivalent to about 310 kg/m^3. Mixing proportions for each mixture were obtained by maximum dry density method, and hence, trial batches with different moisture content (5%, 6%, 7%, 8% and 9% by dry aggregate mass) were made for each percentage of CAE. It is worth mentioning that mass of water taken into account for each percentage of moisture content includes water of the CAE plus pure water, which was considered in determining the water to cement ratios. After making three proctor specimens for each trial batch according to ASTM D1557 [27] and measuring their dry density, the specific moisture-dry density curve was plotted for each of the mixtures. In this curve, the peak point was chosen as the dry density and its corresponding moisture was selected as the optimum mixture moisture content. Assuming 2% air content for the mixtures, the mix design was obtained as shown in Table 3.

2.3. Specimen preparation

As to test the electrical resistivity, water absorption and sorptivity of each mixture, four 200 × 100 mm cylinders were prepared using a vibrating hammer in accordance with ASTM C1435. In the same way, two 100 × 100 × 100 mm cubic specimens were fabricated to assessing water penetration depth of each mixture. The specimens were cured by immersing in water for 90 days and then tested. The cylindrical specimens were cut into three parts, including two discs of 50 mm height and a cylinder of 100 mm height (Fig. 2). Discs were cut from the top (T) and bottom (B) of the cylindrical specimens for the sorptivity test, and mid-cylinders were used to conduct electrical resistivity and water absorption tests.

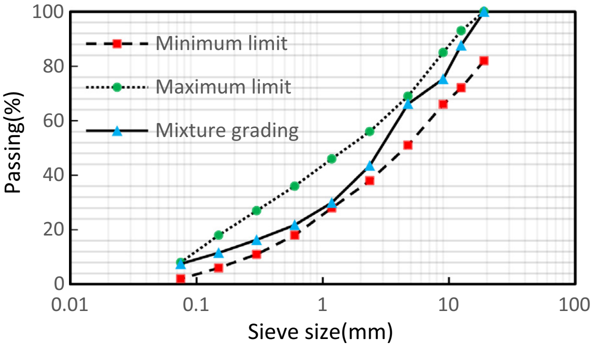

Fig. 1. Gradation of combined aggregate and standard limits according to ACI 211.3R-02 [26].

The conditioning of the discs is of notable importance before starting the test, since the sorptivity values are highly dependent on the moisture conditions of the specimens. In this research, according to ASTM C1585 [28], discs were placed in a temperature of 50 °C for 72 h and then kept in a sealed container for 15 days. After conditioning, all surfaces of the disc, except the cut surface, were insulated with melted paraffin so that the specimens were ready to be tested.

2.4. Testing procedures

2.4.1. Absorption

100 × 100 mm cylinders were tested in accordance with the ASTM C642 [29] to measure the amount of water absorption. Due to the possibility of changing the properties of concrete containing asphalt at 110 °C, the specimens were placed in an oven at a temperature of 50 °C and kept to the mass change less than 0.5%. After measuring the dry mass (*A*), they were again placed in water and kept to the mass change less than 0.5%, then the surface dry mass after immersion (SSD) was measured (*B*). After measuring the values of *A* and *B*, the water absorption percentage was calculated using Eq. (1).

$$Absorption = \frac{B - A}{A} \times 100 \tag{1}$$

2.4.2. Sorptivity

In this test, a special bath is used, with a net at a certain depth, allowing the surface contact of the disc and water. After the end of conditioning and insulating of discs, the bath is filled to the net surface and the specimens are then placed thereon so that the non-insulated concrete surface is in contact with water (Fig. 3).

Table 1
Chemical, mechanical and physical properties of 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(g/cm^3)	–	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 2
Properties of asphalt emulsion.

Type	Setting grade	Color	Density (g/cm^3)	Total solids (%)
Cationic	Rapid	Dark brown	1.01	60

Then, mass of each specimen is measured in 18 stages with certain time steps according to ASTM C1585. Thus, the initial and final sorptivity of specimens are calculated.

In order to calculate the amount of absorbed water, the mass of the specimen is measured at each stage and the water content absorbed in each step is obtained by subtracting its initial mass (mass of insulated specimen before starting the test). Then, by dividing the absorbed water mass by the disc cross-sectional area and the density of the water, the average height of capillary absorption inside the specimen is calculated. Finally, the height of the water is plotted against the square root of time and the slope of the best fitted line passing through the obtained points is considered as the sorptivity. In order to calculate the initial sorptivity, the specimen mass is measured during the first six hours and in 11 steps (with variable time steps). To measure the final sorptivity, the specimen mass is measured over the first eight days and in seven steps (with variable time steps 24 and 48 h).

2.4.3. Water penetration depth

Typically, the water penetration depth test is performed on specimens with a minimum dimension of 150 mm, but in the present study a suitable device was prepared to perform tests on smaller sample sizes (Fig. 4). To use this device, the tank is first filled with water and then the specimen is situated in its place. In order to prevent evaporation of water during the test, the specimen is placed inside the plastic bag. After filling the device with water and placing the specimen, a pump is used to create the proper pressure. To do so, the pressure of the water inside the tank increases to 500 kPa (this value is controlled by the pressure gauge). Once the proper water pressure is reached, it should be ensured that there is no leakage around the specimen and then the water pressure is maintained for 72 h. Next, the specimen is removed from the device and is split; then, the maximum depth of water penetration is measured at 0.1 mm accuracy.

2.4.4. Electrical resistivity

As indicated, the mass of 100 × 100 mm cylindrical specimens in the dry and SSD state is measured. Electrical resistivity test is conducted immediately after measuring the SSD mass. In accordance with ASTM C1760 after 60 s of applying the voltage (i.e., V) to the specimen, the current flowing through the specimen (i.e., I) is measured. The bulk electrical conductivity of the concrete (i.e., σ) can be obtained from Eq. (2). The electrical resistivity is also calculated by inverting the electrical conductivity.

$$\sigma = K\frac{I_1}{V}\frac{L}{D^2} \tag{2}$$

Fig. 2. Cylindrical specimens prepared for water absorption, sorptivity and electrical resistivity tests.

Fig. 3. Bath and net for sorptivity test.

where L is the average specimen length (mm), D is average specimen diameter (mm), and K is conversion factor (1273.2). It is worth noting that the SI unit of conductivity is siemens per meter (S/m). Units of millisiemens per metre (mS/m) are often used for small conductivity values; 1000mS/m = 1S/m.

2.5. Scanning electron microscopy (SEM)

In order to evaluate the effect of CAE on the structure of pores and microstructures of cement paste, the SEM technique was used. Since the transport properties are dependent on the structure of pores, analysis of these images can be very useful in identifying and determining the causes of the changes in the tests' results. The Leo 1450VP model microscope was used in this study as it has the ability to magnify the image between 20× and 300,000×, and is equipped with a secondary electron detector as well as back scatter electrons.

Table 3
Mixture design of RCC (kg/m^3).

Mix.	Cement	CAE	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$_j$:RCC mixture containing j% CAE by cement mass.

Fig. 4. Device prepared to perform the water penetration depth test.

Table 4
Results of the water absorption test.

Mixture	CAE content (%)	Water absorption (%)
B0	0	3.87
B2	2	2.68
B4	4	2.08
B6	6	1.64
B8	8	1.58
B10	10	0.96

3. Results and discussion

3.1. Absorption

Table 4 shows the results of the water absorption test, which results from the average of four RCC specimens. As shown in this table, increasing the asphalt content has reduced the absorption of water in the mixture. Due to full saturation of the specimen during this test, reduction in the amount of water absorption occurs due to two factors: first, filling of concrete voids (including capillary pores and entrapped air voids) with asphalt; second, reduction of entrapped air voids inside the concrete due to the positive effect of asphalt in the compaction of the RCC mixture. Fig. 5 shows the ratio of water absorption of mixtures to water absorption of the control mixture (B0). It is observed that using CAE in the RCC as an admixture is able to considerably reduce water absorption. For example, an increase in CAE content to the value of 10% would result in a decrease to 0.25 of water absorption in the RCC control mixture.

3.2. Sorptivity

The sorptivity for the top and bottom discs of cylindrical specimens is measured and the results are described in Table 5. By increasing the CAE and thereby asphalt content in the RCC mixtures, a significant reduction in their initial and final sorptivity occurs, indicating a significant influence of asphalt on the structure of pores. Using low content of asphalt could fill the capillary pores and cover the air void walls. However, with increasing asphalt content, the volume of filled pores would increase so that the amount of initial sorptivity in the RCC mixture containing 10% CAE reaches about 0.05 of the control mixture (Fig. 6). The reduction in the final sorptivity ratio (the ratio of the sorptivity of the mixtures to the control mixture) of the RCC mixtures is less than the reduction of their initial sorptivity ratio; this difference is evident with the comparison of Fig. 6 and Fig. 7. The sorptivity ratio in the top and bottom discs of the B2, B4 and B6 mixtures is approximately the same. However, with increasing the CAE content to 8%, it is observed that the difference between the sorptivity ratio of the top and bottom discs of the specimens increases so that with increasing the CAE content to 10%, this difference becomes more evident. This change can be due to the high asphalt content in these mixtures and movement of excess asphalt to the upper disc of the specimen during the compaction process. As shown in Table 5, the amount of sorptivity of the bottom disc of the specimen is less than that of the top disc, which can be attributed to the more compaction of the bottom part of the specimen.

3.3. Water penetration depth

The results show a decreasing trend in the amount of water penetration depth in the RCC mixtures by increasing their asphalt content (Table 6). Similar to the results of other tests in this study, the RCC transport properties have improved by increasing the asphalt content. However, decreasing the water penetration depth inside the RCC owing to water pressure is of importance since it ensures that asphalt performance is not impaired when the hydrostatic pressure is high (e.g. in the roller compacted concrete dam), and that it plays a positive role in improving the transport properties of the RCC mixture. In Fig. 8, water penetration depth ratios (the water penetration depth of the RCC mixtures containing asphalt divided by that of the control mixture) is plotted. It can be seen that increasing the use of asphalt in the RCC not only has a positive effect on the reduction of water penetration depth, but also the relative observed decrease in the results of water penetration depth is more noticeable compared with that of the water absorption test.

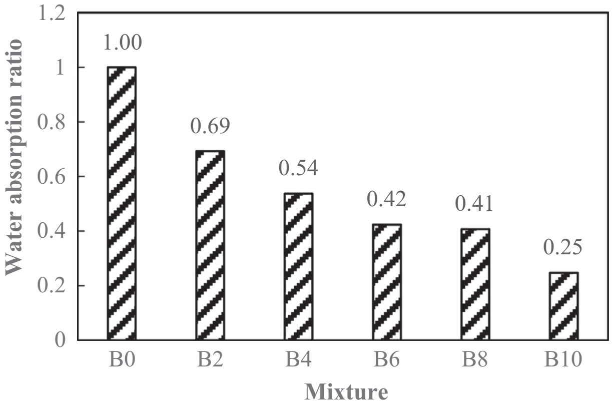

Fig. 5. Water absorption ratio of RCC mixtures containing different amounts of CAE.

Table 5
Result of Sorptivity test for the top and bottom parts of cylindrical specimens ($mm/\sqrt{min}$).

Mixture	CAE content (%)	Sorptivity			
		Initial		Final	
		Top	Bottom	Top	Bottom
B0	0	0.3492	0.0923	0.0268	0.0182
B2	2	0.2064	0.0648	0.0182	0.0124
B4	4	0.1641	0.0423	0.0124	0.0089
B6	6	0.0524	0.0144	0.0120	0.0085
B8	8	0.0210	0.0113	0.0054	0.0085
B10	10	0.0186	0.0085	0.0031	0.0062

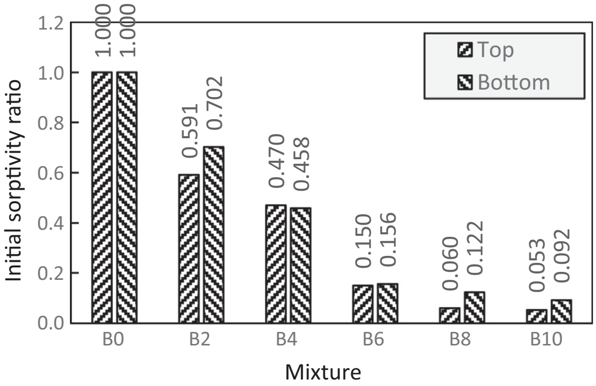

Fig. 6. Initial sorptivity ratio of the RCC mixtures containing different amounts of CAE.

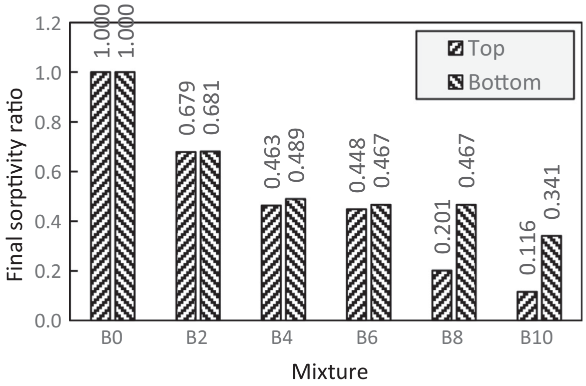

Fig. 7. Final sorptivity ratio of the RCC mixtures containing different amounts of CAE.

Table 6
Water penetration depth of the RCC mixtures with different CAE content.

Mixture	CAE content (%)	Depth of penetration (mm)
B0	0	38.8
B2	2	30.1
B4	4	15.3
B6	6	15.4
B8	8	7.6
B10	10	5.6

3.4. Electrical resistivity

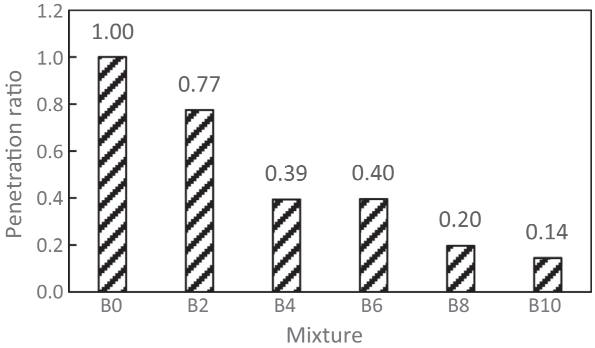

Fig. 8. Penetration depth ratio of the RCC mixtures with different CAE content.

The electrical resistivity mainly depends on the pores connectivity and the possibility of the displacement of the ions within the concrete. Therefore, increasing the electrical resistivity in the mixtures can be attributed to the blocking of the pores network within the concrete with asphalt and thus the impossibility of displacement of ions. Reducing the connection of concrete pores can prevent movement of various destructive materials (e.g. soluble salts) into the concrete and prevent the development of ice crystals inside. The results of the electrical resistivity of the RCC mixtures are given in Table 7. In addition, Fig. 9 shows the ratio of electrical resistivity of the mixtures containing asphalt to that of the control mixture.

Comparatively, the electrical resistivity test is much faster than water absorption and penetration, and sorptivity. Although electrical resistivity is an indicator of the pores connectivity, its results can be used to evaluate other transport properties of concrete. The use of this non-destructive test can be very beneficial in evaluating the concrete transport properties. Therefore, the relationship between the results of this test and other concrete transport properties is of particular importance. In order to achieve this, the Pearson's correlation (r) and intrinsically linear regression analyses were applied to find strengths of the relationships among the results and developing the proper models, respectively. The models were selected based on maximum coefficient of determination values (R^2) and analysis of residuals. Table 8 and Fig. 10, respectively, represent the Pearson's correlations and characteristics of the models and their illustrations. It is observed that there are strong negative linear relationships between the electrical resistivity (independent variable) and the results of other applied

Table 7
Electrical resistivity of the RCC mixtures containing different CAE content.

Mixture	CAE content (%)	Electrical resistivity (Ωm)
B0	0	97.3
B2	2	330.5
B4	4	521.7
B6	6	536.4
B8	8	769.6
B10	10	1165.7

Table 8
Pearson's correlations and developed models between electrical resistivity and water absorption, penetration depth and sorptivity.

Properties	Model	R^2	r	
Initial sorptivity-resistivity	Top	$y = -0.139\ln(x)+0.9767$	0.87	−0.82
	Bottom	$y = -0.035\ln(x)+0.2502$	0.83	−0.81
Final sorptivity-resistivity	Top	$y = -0.01\ln(x)+0.0712$	0.94	−0.9
	Bottom	$y = -0.005\ln(x)+0.0397$	0.91	−0.83
Penetration-resistivity		$y = -14.59\ln(x)+107.87$	0.92	−0.85
Absorption-resistivity		$y = -1.178\ln(x)+9.2854$	0.97	−0.91

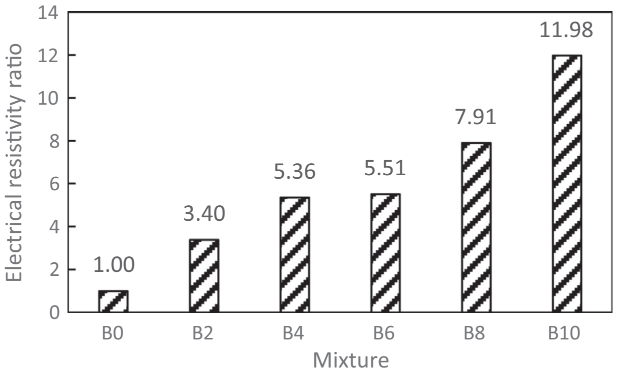

Fig. 9. Electrical resistivity ratio of the RCC mixtures containing different CAE content.

tests (dependent variables) with high R^2 values in logarithmic form of independent variable.

3.5. Scanning electron microscopy

Figs. 11 and 12 show the SEM images for the RCC mixtures with a magnification of 1000 X. By comparing the mixtures B0 and B4 in Fig. 11, it is observed that the walls of the pores in the B4 are coated with a layer of asphalt. This layer can be a reason for reduced sorptivity, as well as improving other transport properties of the RCC mixtures modified with asphalt. According to Fig. 12, which represents the mixtures B6 and B8, it is observed that with increasing the asphalt content from 6% to 8%, coating of the hydration products is increased and the pores are filled with asphalt, which results in a significant improvement in the transport properties. Fig. 13 shows the RCC mixtures B0 and B4 with a 5000X magnification; it can be seen that the structure of the capillary pores is

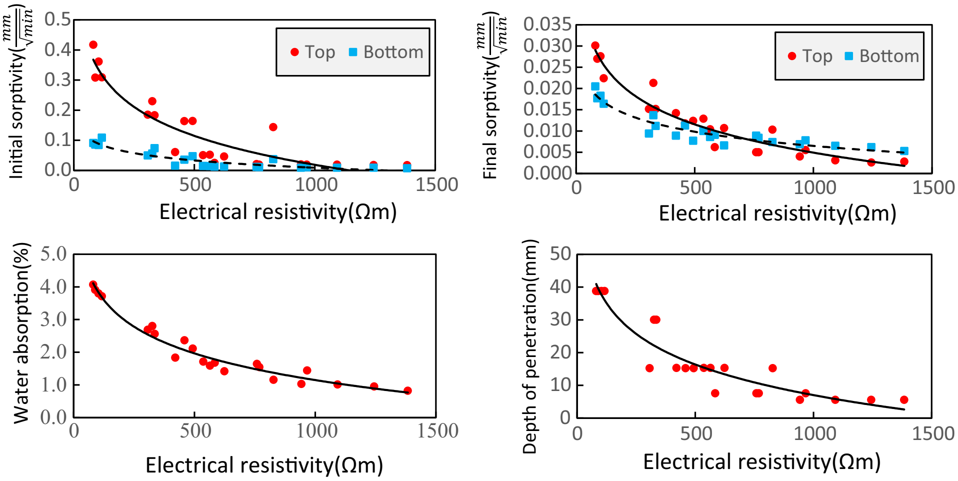

Fig. 10. Relationships between electrical resistivity and water absorption, penetration depth and sorptivity.

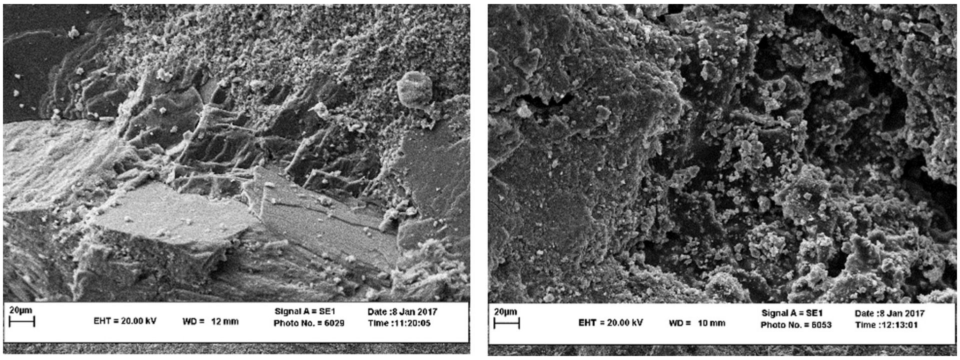

Fig. 11. SEM images for the RCC mixtures B0(left) and B4(right) with magnification of 1000×.

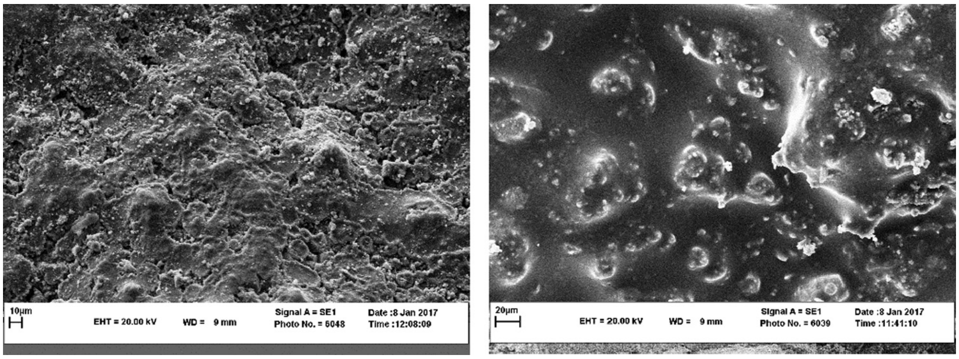

Fig. 12. SEM images for the RCC mixtures B6(left) and B8(right) with magnification of 1000×.

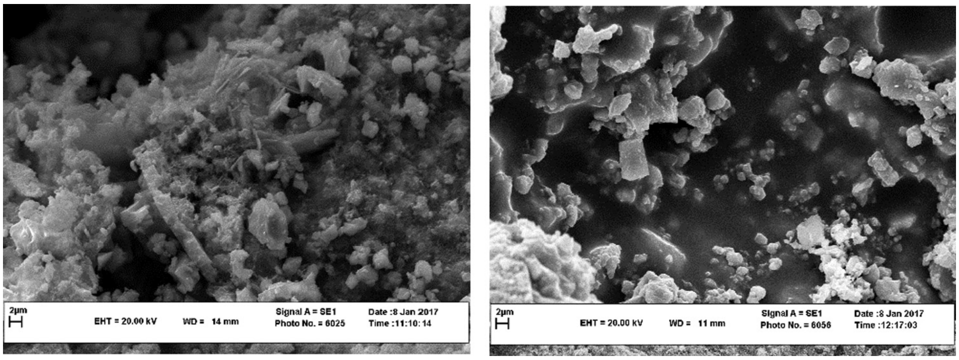

Fig. 13. SEM images for the RCC mixtures B0(left) and B4(right) with magnification of 5000×.

quite affected by the asphalt. By comparing these two figures, the complete filling of the capillary pores in the areas coated with asphalt can be observed.

3.6. Analysis of variance (ANOVA)

Generally, the results indicate that the transport properties of the RCC mixtures containing CAE are improved. Nevertheless, this improvement can be due to either random errors in laboratory conditions (error in fabricating specimens or carrying out tests) or positive effect of CAE on the transport properties of the RCC mixtures. Consequently, in order to examine this hypothesis, analysis of variance (ANOVA) at a significance level of 5% was conducted. According to Table 9, which shows the ANOVA results, it is reasonable to say that all of the transport properties of the RCC due to adding CAE are significantly improved (p-value less than 0.05). Also, Dunnett comparison procedure was employed to determine the mixtures which had a significant difference in comparison with the control mixture (B0). In this method, each of the mixtures containing different asphalt content was compared with the control mixture and significant differences in the results of the tests were assessed. The results of this analysis revealed that sorptivity and absorption in all the asphalt-containing RCC mixtures were significantly improved compared to the control mixture, but it was the case in the RCC mixtures containing equal or more than 4% asphalt for the penetration depth and electrical resistivity.

4. Conclusions

In the present study, various percentages of CAE (2% to 10%) were used as an admixture in the manufacturing process of the RCC mixture, and the transport properties of these mixtures were investigated. The transport properties of concrete can control its durability in a variety of environmentally harsh conditions. Therefore, due to the large surface of the RCCP and its high probability of being exposed to destructive conditions, the characteristics of the RCC are of great importance. In conclusion, the following findings are worthy of note:

The results indicate that the transport properties of the RCC mixtures are improved if asphalt is added. Analysis of variance confirms this significant positive effect at 95% confidence level, and also, SEM images justify how the results of the transport properties are changed by modifying the RCC with CAE.

Considering the importance of non-destructive tests, for the evaluation of RCC transport properties, proper models were developed based on non-destructive electrical resistivity test. Using these models, it is possible to obtain the estimations of water absorption, sorptivity and water penetration depth of the RCC mixtures.

According to the transport properties and SEM images of the RCC mixtures, it is determined that using asphalt has a positive effect on the structure of hardened cement paste pores and reduces the amount of capillary pores.

The CAE can be an appropriate admixture for using in the RCCP in areas where the possibility of base layer saturation is high, since the amount of destructive solutions being absorbed by the RCC concrete surface from this layer could be directly reduced because of filling the capillary pores with asphalt.

Significant improvement in the penetration property of the RCC concrete against water pressure indicates the proper performance of this admixture under high hydrostatic pressure. The RCC used in the construction of the dam is an application of this type of

Table 9
Analysis of variance and Dunnett comparison at 95% confidence level.

Source of variance			Source of variation	DF	Adj SS	Adj MS	F-value	P-value
Sorptivity	Initial	Top	CAE content	5	0.32972	0.065945	103.96	.000
			Error	16	0.01015	0.000634		
			Total	21	0.33987			
		Bottom	CAE content	5	0.021855	0.004371	98.83	.000
			Error	16	0.000708	0.000044		
			Total	21	0.022562			
	Final	Top	CAE content	5	0.001434	0.000287	61.88	.000
			Error	16	0.000074	0.000005		
			Total	21	0.001508			
		Bottom	CAE content	5	0.000359	0.000072	38.26	.000
			Error	16	0.000030	0.000002		
			Total	21	0.000389			
Electrical resistivity			CAE content	5	2,590,542	518,108	23.74	.000
			Error	16	349,194	21,825		
			Total	21	2,939,736			
Absorption			CAE content	5	20.451	4.09016	41.84	.000
			Error	16	1.564	0.09776		
			Total	21	22.015			
Penetration			CAE content	5	1701.49	340.30	24.55	0.001
			Error	6	83.15	13.86		
			Total	11	1784.64			

Mixture	Sorptivity (lower; upper)				Absorption (lower; upper)	Electrical Resistivity (lower; upper)	Penetration depth (lower; upper)
	Initial		Final				
	Top	Bottom	Top	Bottom			
B0	(0.322; 0.375)	(0.085; 0.099)	(0.024; 0.029)	(0.016; 0.019)	(3.54; 4.20)	(59.26; 253.91)*	(32.36; 45.24)*
B2	(0.168; 0.244)	(0.054; 0.074)	(0.015; 0.021)	(0.010; 0.014)	(2.21; 3.15)	(109.05; 551.95)*	(23.61; 36.49)*
B4	(0.137; 0.190)	(0.035; 0.049)	(0.010; 0.014)	(0.007; 0.010)	(1.74; 2.41)	(365.00; 678.00)	(8.81; 21.69)
B6	(0.025; 0.079)	(0.007; 0.021)	(0.009; 0.014)	(0.007; 0.009)	(1.30; 1.97)	(379.80; 693.00)	(8.91; 21.79)
B8	(0.005; 0.047)	(0.004; 0.018)	(0.003; 0.007)	(0.007; 0.010)	(1.24; 1.90)	(613.00; 926.20)	(1.16; 14.04)
B10	(0.008; 0.045)	(0.001; 0.015)	(0.001; 0.005)	(0.004; 0.007)	(0.62; 1.28)	(1009.10; 1322.30)	(0.84; 12.04)

Means not labeled with the (*) are significantly different from the control level mean.

concrete under high pressure hydrostatic pressure. Of course, the mixture design for this type of RCC using its given method should be repeated.

Results of ANOVA show that if equal or more than 4% CAE is used in RCC, it can be expected to improve all the transport properties of this mixture and accordingly its durability.

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References

[1] ACI 207.5, Report on roller-compacted mass concrete, American Concrete Institute, 2011, 71.

[2] ACI 325.10, Report on roller-compacted concrete pavements, American Concrete Institute, 1995, 32.

[3] D. Harrington, F. Abdo, W. Adaska, C. V.Hazaree, H. Ceylan, Guide for roller-compacted concrete pavements, 2010.

[4] A.M. Neville, Properties of concrete, Longman London, 1995.

[5] P.A. Claisse, Introduction, Transport Properties of Concrete, Woodhead Publishing, Oxford, 2014. PP. xxi–xxiii.

[6] Front Matter A2 – DULLIEN, F.A.L, Porous Media (2nd Ed.), Academic Press, San Diego, 1992, p. iii.

[7] M.A. Wilson, M.A. Carter, W.D. Hoff, British standard and RILEM water absorption tests: a critical evaluation, Mater. Struct. 32 (8) (1999) 571–578.

[8] R.N. Yong, A.-M.O. Mohamed, B.P. Warkentin, Principles of Contaminant Transport in Soils, Elsevier Science Publishers, 1992.

[9] A. Boddy, E. Bentz, M.D.A. Thomas, R.D. Hooton, An overview and sensitivity study of a multimechanistic chloride transport model, Cem. Concr. Res. 29 (6) (1999) 827–837.

[10] J. Kropp, H.K. Hilsdorf, H. Grube, C. Andrade, L.-O. Nilsson, transport mechanisms and definitions in performance criteria for concrete durability, E & FN SPON, London, 1995.

[11] R.J. Gummerson, C. Hall, W.D. Hoff, Water movement in porous building materials—II Hydraulic suction and sorptivity of brick and other masonry materials, Build. Environ. 15 (2) (1980) 101–108.

[12] ACI 201.2, Guide to Durable Concrete, American Concrete Institute, 2001, p. 41.

[13] G.S.S.K.R.J. J.W. John, C. McCarter, Malcolm Electrode Configurations for Resistivity Measurements on Concrete, Mater. J. 106(3).

[14] A. Karimpour, Effect of time span between mixing and compacting on roller compacted concrete (RCC) containing ground granulated blast furnace slag (GGBFS), Constr. Build. Mater. 24 (11) (2010) 2079–2083.

[15] H. Chetan, W. Kejin, C. Halil, G. Kasthurirangan, Capillary transport in RCC: water-to-cement ratio strength, and Freeze-Thaw resistance, J. Mater. Civil Eng. 23 (8) (2011) 1181–1191.

[16] A. Yerramala, K. Ganesh Babu, Transport properties of high volume fly ash roller compacted concrete, Cem. Concr. Compos. 33 (10) (2011) 1057–1062.

[17] A. Mardani-Aghabaglou, Ö. Andiç-Çakir, K. Ramyar, Freeze–thaw resistance and transport properties of high-volume fly ash roller compacted concrete designed by maximum density method, Cem. Concr. Compos. 37 (2013) 259–266.

[18] S.A. Ghahari, A. Mohammadi, A.A. Ramezanianpour, Performance assessment of natural pozzolan roller compacted concrete pavements Case Studies in Constr. Mater.

[19] A.A. Ramezanianpour, A. Mohammadi, E.R. Dehkordi, Q.B. Chenar, Mechanical properties and durability of roller compacted concrete pavements in cold regions, Constr. Build. Mater. 146 (2017) 260–266.

[20] M. Kosior-Kazberuk, W. Jezierski, Surface scaling resistance of concrete modified with bituminous addition, J. Civil Eng. Manage. 10 (1) (2004) 25–30.

[21] M. Boltryk, E. Pawluczuk, W. Rutkowska, Influence of asphalt addition and consolidation method on the durability of cement concrete, J. Civil Eng. Manage. 17 (4) (2011) 476–482.

[22] M. Bołtryk, D. Małaszkiewicz, Application of anionic asphalt emulsion as an admixture for concrete, Constr. Build. Mater. 40 (2013) 556–565.

[23] M. Bołtryk, K. Falkowski, E. Pawluczuk, A report on the fabrication of concrete pavement with the application of anionic bitumen emulsion, Constr. Build. Mater. 154 (2017) 1004–1014.

[24] B. Huang, X. Shu, E.G. Burdette, Mechanical properties of concrete containing recycled asphalt pavements, Mag. Concr. Res. 58 (5) (2006) 313–320.

[25] B. Huang, X. Shu, G. Li, Laboratory investigation of portland cement concrete containing recycled asphalt pavements, Cem.Concr. Res. 35 (10) (2005) 2008–2013.

[26] ACI 211.3, Guide for Selecting Proportions for No-Slump Concrete, American Concrete Institute, 2002, p. 26.

[27] ASTM D1557-12e1, Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft3 (2,700 kN-m/m3)), ASTM International, West Conshohocken, PA, 2012.

[28] ASTM C1585 – 13, Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes, ASTM International, West Conshohocken, PA, 2013.

[29] ASTM C642 – 13, Standard Test Method for Density, Absorption, and Voids in Hardened Concrete, ASTM International, West Conshohocken, PA, 2013.