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Short communication

Performance assessment of natural pozzolan roller compacted concrete pavements

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ABSTRACT

Concrete pavement is cost effective and beneficial because of its sustainability and durability. The maintenance and renovation periods for such pavement compared to other pavements are relatively long; however, a significant issue with pavements, especially roller compacted concrete pavements (RCCP), is salt scaling which occurs due to saline solutions such as deicer salts. In the present work, the performance of RCC containing a natural pozzolan called Trass, as a supplementary cementitious material, and an air-entraining agent for salt scaling was investigated. Mechanical and durability tests were performed on specimens containing a water to binder ratio of 0.32, with and without Trass, and an air-entraining agent. It was concluded that, Trass could not improve the compressive and tensile strengths, however, the permeability was improved. Moreover, the amount of mass loss due to salt scaling was not decreased. In all concrete mixtures, using a suitable amount of an air-entraining agent to maintain a total air content of 4.5–5% was found to be necessary for producing RCC containing Trass.

1. Introduction

Advantages of using RCC, such as a high-rate of production and low cost [1], have increased the incidence of its use, especially in pavement construction projects for heavy weight vehicles like airports [2]. Roller compacted concrete for pavement (RCCP) has ingredients similar to those found in conventional concrete. However, since it is a non-slump concrete, vibratory compaction [3] has to be used in order to compact each 25 cm layer of concrete slabs; this work should be done by equipment used for asphalt paving [4]. Problems reported for RCCP are the rigidity and relative tendency to crack because of plastic shrinkage and low tensile strength [5]. To decrease the possibility of thermal cracking, RCCP is produced with low Portland cement content, and consequently, with high amounts of supplementary cementitous materials such as, fly ash, silica fume, and blast furnace slag [6,7]. Much work has been conducted on improving the frost resistance of RCCP through an air-entraining agent [8]. The amount of air entraining admixtures that provides substantive air voids for countering the effects of freezing and thawing (F–T) cycles on concrete specimens have been studied as well [9]. Production of RCCP with an air-entraining agent is not feasible in some projects due to the inherent difficulty of entraining air in dried concrete [10].

Some research projects have been performed on using pozzolans and natural pozzolans in RCCP. It has been found that in specimens containing pozzolans and with a compressive strength higher than 40 MPa, resistance to F–T cycles is acceptable [11];

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however, the water to cement ratio should be limited in order to prevent concrete bleeding. Silica fume, as one type of pozzolan, can improve the resistance of concrete specimens to F–T cycles [12], meanwhile, the percentage of silica fume should be limited at 5% to 7% to maintain durability requirements [13]. Higher compressive strength due to adding silica fume leads to higher F–T resistance [14]. Using slag, as another pozzolan, in concrete mixture shows similar results [15]. Fly ash, on the other hand, reduces the resistance to F–T cycles [16,17], which could be due to bleeding and segregation on the surface of the specimens because of the pozzolans [18,19]. Investigations of the effects of supplementary cementitous materials on low-cement RCCP have shown these materials lead to a reduction in compressive strength and resistance to F–T cycles [20].

According to a recent survey, the use of deicing salts on concrete pavements is growing, especially in cold regions of the USA and Canada [21]. Therefore, the pavements should be constructed not only to resist F–T cycles but also to be more resistant to scaling in the presence of salt solutions and deicers. Therefore, it is a promising idea to introduce a feasible way of improving the deicer salt scaling resistance of RCCP by using supplementary cementitous materials. Trass, as a natural poozzolan is cost beneficial. It is a readily available natural pozzolans and this natural pozzolan reacts well with air-entraining agents. Herein, in this study, the effect of Trass, as a natural pozzolan, on workability, and mechanical and durability properties of air-entrained and non-air-entrained RCC is investigated.

2. Experimental program

2.1. Materials and mixture design

Specimens were cast with typical type I Portland cement which meets ASTM C150 specifications [22]. 20% by weight of cement was replaced with Trass natural pozzolan, and specimens with a 0.32 water/binder ratio were cast. Local river sand as fine aggregate and crushed stone as coarse aggregate with maximum aggregate size of 4.75 mm and 19 mm were used according to the ACI recommendation. The densities of fine and coarse aggregates are measured as 2520 kg/m^3 and 2580 kg/m^3, with water absorptions of 2.8% and 1.5%, respectively. The characteristics of cement and Trass are illustrated in Table 1. In order to attain workability in all mixtures, a liquid polycarboxylic ether-base as superplasticizer (SP) was used. The SP used in this research had a specific gravity of 1.18 and 40% solid content.

In this research, an air-entraining agent with specific gravity and solid content of 1.2 and 45% was used. Considering the maximum aggregate size of 19 mm and “moderate exposure”, a proposed dosage of suitable air-entraining agent is 0.04% to 0.1% by weight of cement [23]. After trial and error process in casting samples with the preferred total air content which is 4.5–5% [24], the preferred dosage of the air-entraining agent was chosen as 0.06% by cement weight. The calculation of air content percentage is discussed in the last section of this paper.

For each test three samples were cast. Specimens were cast regarding the mixture proportions given in Table 2. R-32 denotes specimens with no air-entraining agent and pozzolan ($W/C = 0.32$), and T-A-32 denotes specimens with Trass natural pozzolan and air-entraining agent ($W/C = 0.32$). Having batched the materials in a mixer, each mixture design was tested for workability by VeBe test method, which is suitable for RCCP [25,26].

2.2. Testing procedure and specimen preparation

Compressive and tensile strength tests were carried out on 150 mm × 300 mm cylindrical specimens at the ages of 28, 90, and 180 days in accordance with ASTM C39 and ASTM C496 [27,28]. 150 mm × 150 mm cubic specimens were molded to be tested for water penetration and sorptivity according to BS EN 12390-8 and BS EN 480-5 [29,30]. Moreover, ASTM C672 [31] salt scaling test was performed on two disk specimens of 450 cm^2 area and 7.5 cm thickness. All specimens were molded in accordance with ASTM

Table 1
Chemical and physical characteristics of the cement and filler.

Chemical composition (%)	Cement	Trass
CaO	62.08	3.36
SiO_2	21.10	67.2
Al_2O_3	4.18	14.14
Fe_2O_3	3.34	2.96
MgO	3.79	1.6
SO_3	2.84	0.068
K_2O	0.69	2.5
Na_2O	0.14	4.3
Pozzolanic activity at 7 days	–	57%
Pozzolanic activity at 28 days	–	68%
Loss on ignition (%)	3.00	8.5
Physical properties		
Specific gravity	3.17	3.10
Blaine fineness (cm^2/g)	3519	3200

Table 2
Mixture proportions for RCCP.

Sample ID	Binder (kg/m^3)		Ratio of the filler to cement (%)	Aggregate (kg/m^3)			Air-entraining agent by cement weight/volume (%)	Super plastisizer dosage by cement weight (%)
	Cement	Filler		Fine Agg. (FA)	Coarse Agg. (CA)	Total		
R-32	330	0	0	1180	788	1968	0/0	0
R-A-32	330	0	0	1158	772	1930	0.06/0.15	0
T-32	264	66	25	1161	774	1935	0/0	0.8
T-A-32	264	66	25	1138	759	1897	0.06/0.15	0.6

C1176, which is designated to RCCP [32], and were cured in a room with 50 ± 5% relative humidity and 23 ± 2 °C temperature. The specimens were put in an F–T chamber for a long period of freezing and thawing cycle, i.e. −18 °C for 18 h and 23 °C for 6 h. In order to measure the distribution of air voids and the air content percentage in specimens, the vertical profile of each 150 mm × 300 mm cylindrical specimen was scanned, and the distribution and percentage of air voids were measured by Bubble Counter Software using the method found in ASTM C457-12 [33].

3. Results and discussion

3.1. Fresh concrete properties

To indicate the workability of RCC mixtures, the VeBe test, which is suitable for mixture designs and specimens with no slump, was performed. The test was performed on three samples for each mixture design. According to the results shown in Fig. 1, the value of the VeBe test, when using Trass, is higher than that of the reference concrete. The obtained results indicate that the workability has been reduced, possibly due to the high water absorption properties of natural pozzolans; consequently, a larger amount of superplasticizer is needed to attain the VeBe results compared with the mixtures with no Trass. When using 0.06% air-entraining agent, the VeBe value for T-A-32 is 38 s, which is 10% lower than that of T-32, the same mixture without air-entraining agent. This shows that the effect of the air-entraining agent in the workability of plain concrete is similar to the specimens with Trass, and when more air bubbles or voids are available in the concrete microstructure, a higher VeBe value is achieved, and this problem could be alleviated by adding extra superplasticizer.

3.2. Hardened concrete properties

3.2.1. Compressive and tensile strengths

Results of compressive strength, relative compressive strength, and splitting tensile strength are presented in Figs. 2–4 , respectively. The tests were performed on three samples for each mixture design. Regarding the results, the compressive strength of specimens containing Trass is 35% lower than that of the plain concrete at early ages which could be due to the low pozzolanic activity. At early ages, low pozzolanic activity reduces the participation of cement materials in hydration. However, gradually, at the late age of 90 days, the compressive strength of T-32 is relatively improved and is 14% lower than that of R-32. This indicates the fact

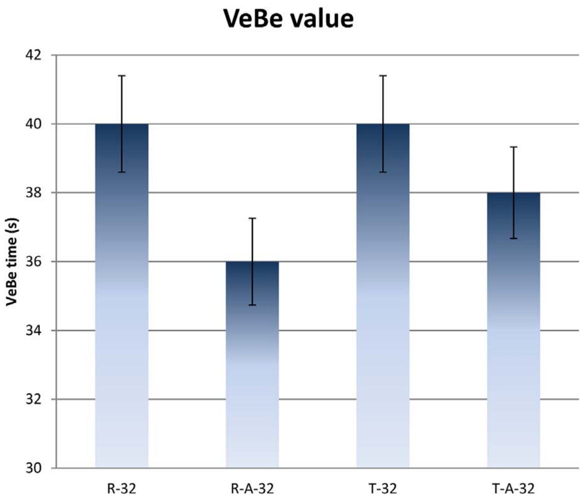
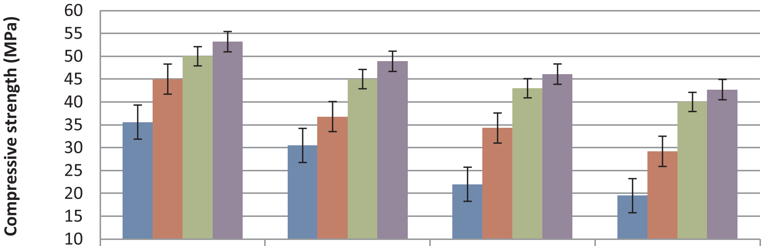


Fig. 1. Results of the VeBe test for fresh concrete.



	R-32	R-A-32	T-32	T-A-32
7 days	35.6	30.5	22	19.5
28 days	45	36.8	34.3	29.2
90 days	50	45	43	40
180 days	53.2	48.9	46.1	42.7

Fig. 2. Results of the compressive strength for the specimens at the age of 28 days.

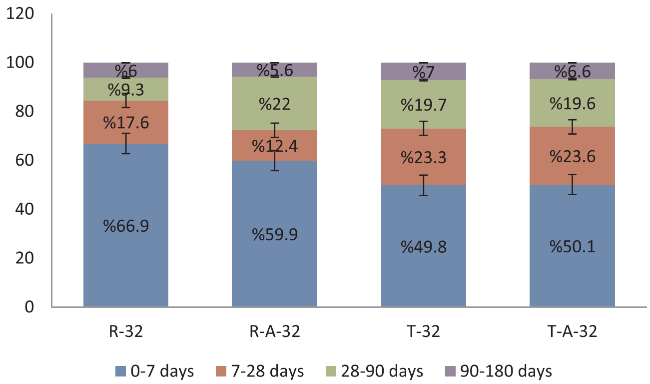


Fig. 3. Relative compressive strength for the specimens at the age of 7–180 days.

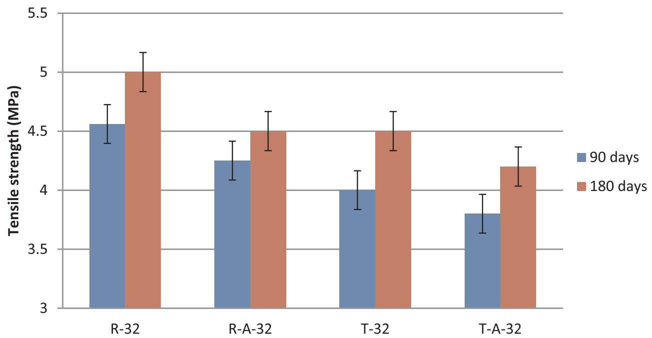


Fig. 4. Results of tensile strength for all of the specimens at the age of 90 and 180 days.

that Trass has compensated its lag in production of C–S–H gel. According to Fig. 3, until the age of 7 days, the percentage of compressive strength improvement for the specimens which contain natural pozzolan is 17% lower than that of the plain concrete; however, the percentage is relatively stable from 28 days to 90 days. Moreover, due to the fact that tensile strength has a direct relationship with compressive strength, the same trend can be seen from the results. Tensile strength values signify that, the tensile strength of T-32 is 12% lower than that of R-32. The 0.06% air-entraining agent is an important factor in the decrease of compressive and tensile strengths. According to the results, the compressive and tensile strengths for T-A-32 is 7% and 5% lower than that of T-32 at the age of 90 days, which is probably related to a higher void content due to the air-entraining agent. Furthermore, T-A-32 compared with R-A-32 has 11% and 10% higher compressive and tensile strengths, respectively, at the late age of 90 days; this could be due to the filling effect of natural pozzolan on the voids, and consequently, reduction in their volume.

3.2.2. Water penetration

A Water penetration test was carried out in order to measure permeability. The test was performed on three samples for each mixture design. Specimens with higher durability and surface strength had a lower depth of water penetration because of a lower rate of chloride ion penetration. The results of water penetration depths are illustrated in Fig. 5. The results indicate that, at the age of 90

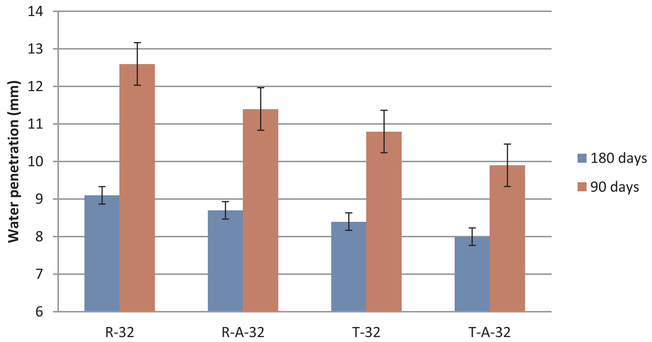


Fig. 5. Water penetration depth for the specimens at the age of 90 and 180 days.

days, the specimen with Trass has a water penetration depth of 10.8 mm, 14% lower than that of R-32. This could be due to the reduction of amount of cement by 20% of its weight in the specimens containing supplementary cementitous materials. Dilution effect and low pozzolanic activity of Trass are responsible for higher permeability at early ages; however, at the age of 180 days, the water penetration depth of both plain concrete and concrete containing pozzolan are relatively the same. On the other hand, when 0.06% air-entraining agent is used, the water penetration depth for both types of mixtures is decreased. The lower depth could be due to more porosity caused by the air-entraining agent. However, due to the filling ability and gradual formation of C–S–H gel in the presence of Trass, the water penetration depth for T-A-32 is 13% lower than that of R-A-32 at the age of 90 days. This could lead to less capillary porosity in the meantime. No significant differences in water penetration results were seen among the 4 types of mixtures at the age of 180 days, which could be due to the slow pozzolanic reaction of Trass that fills the voids by making tortuous paths of water to be absorbed into.

3.2.3. *Sorptivity*

The test was performed on three samples for each mixture design. Results of sorptivity coefficients (S), defined from BS EN 480-5 [29] equation as stated in the following, are illustrated in Fig. 6:

$$Q = A^*(C + S^*t0.5) \quad (1)$$

where Q is the amount of water absorbed; A is the cross section of the specimen that is in contact with water; t is the time in seconds; C is the constant coefficient; and S is the sorptivity coefficient of the specimen (m/s$^{0.5}$).

Regarding the sorptivity coefficient as another index for the permeability of concrete, Trass could considerably decrease the coefficient. The sorptivity coefficient for R-32 is significantly higher than that of T-32 at the age of 90 days. Due to the pozzolanic activity of Trass, the value of S for T-32 is 14% lower than that of R-32, which signifies a reduction in capillary porosity and loss of connectivity in the pore structure and has been discussed in concrete technology related discussions elsewhere [34–37]. Besides, after using the air-entraining agent, the value of S has decreased because of the higher amount of porosity. The value of S for T-A-32 is 11.6(10^{-6}) (m/s$^{0.5}$) which is 13% lower than that of R-A-32. This could be due to the capability of Trass to reduce the capillary porosity and conductivity of the pores, and the results are in agreement with the results obtained from the water penetration test.

3.2.4. *Deicer salt scaling*

After 50 cycles of F–T, the mass scaled off the surface of the specimens was weighted. The test was performed on three samples for each mixture design. The results of the deterioration rate of the deicer salt scaling test and the cumulative weight loss for the mass scaled off the surface of the specimens cured for 28 days are given in Table 3 and Fig. 7, respectively. The same results shown in Fig. 7 indicate that when exposed to a deicer salt solution, the mass loss for T-32 is 51% higher than that of R-32, as Trass has shown a low reaction with cement particles. It can be concluded that while using Trass, the compressive strength is not reciprocally related to the

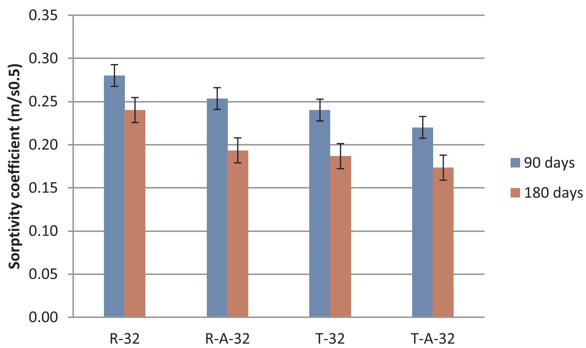


Fig. 6. Sorptivity coefficient for the specimens at the age of 90 and 180 days.

Table 3
Deterioration rate and weight loss percentage that scaled off the surface.

Sample ID	No.	Number of cycles										Cumulative weight loss (kg/m^2)
		Weight loss at each cycle (%)										
		5	10	15	20	25	30	35	40	45	50	
R-32	1	1	1	1	2	2	2	2	2	2	2	0.57
	2	1	1	1	2	2	2	2	2	2	2	
	(%)	2.22	4.93	12.34	20.49	29.62	41.49	54.77	69.29	82.23	100	
R-A-32	1	1	1	1	1	2	2	2	2	2	2	0.41
	2	1	1	1	2	2	2	2	2	2	2	
	(%)	1.76	4.29	10.5	15.23	24.95	37.12	47.38	55.44	78.71	100	
T-32	1	1	2	2	3	3	3	3	3	3	4	1.15
	2	1	2	3	3	3	3	3	3	4	5	
	(%)	2.80	6.11	19.43	32.13	37.94	54.95	69.36	78.83	90.62	100	
T-A-32	1	1	2	2	3	3	3	3	3	4	4	0.92
	2	1	2	2	2	3	3	3	3	3	4	
	(%)	2.23	5.17	16.56	25.08	33.65	48.95	61.05	73.17	85.47	100	

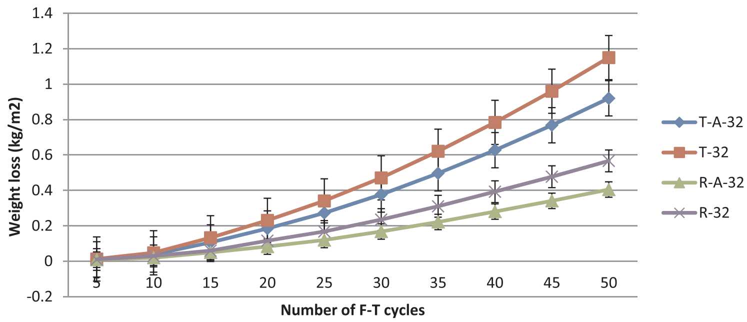


Fig. 7. The results of the salt scaling test.

mass loss of the specimens. For R-32, R-A-32, and T-A-32, the mass loss is below the threshold of 1 kg/m^2 which is required for good performance according to the Swedish standard [10]. On the other hand, when the air-entraining agent is added, the overall mass loss for the air-entrained specimens is lower than that of the non-air entrained specimens. As it goes below 4 °C, the air voids may provide more spaces to accommodate expanding water, i.e. about 10% of their volume, which is the main cause of the cracking, delaminating, or deteriorating of concrete structures. The mass loss for T-A-32 is 0.92 kg/m^2 which is 56% higher than that of R-A-32; therefore, R-A-32 has the highest salt-scaling resistance. In this condition, the compressive strength is not reciprocally related to the results of the salt scaling test. Therefore, 0.06% air-entraining agent by weight of cement, which provides the total air content of 4.5–5%, is sufficient if using Trass; however, for each type of air-entraining agent, this value may change in order to provide the total air content of 4.5–5%.

According to a recent study by Nili and Zaheri [14], by using silica fume, higher compressive strength could lead to a lower mass loss due to F–T cycles. This is reported to be due to the improvement of the strength of the surface of the specimen as well as decreasing its permeability; however, by using slag, higher compressive strength did not lead to a higher F–T resistance [15]. Therefore, by improving compressive strength through materials that decrease surface permeability, usually the mass loss due to F–T cycles can be limited. In fact, using Trass leads to the creation of clustered air voids which accordingly creates more F–T and salt scaling mass loss values; therefore, as the compressive strength has not been improved while using Trass, the mass loss value in the F–T cycles has not been reduced either, although the overall permeability has improved. All the results were in accordance with what was observed by monitoring the surface of the specimens exposed to the F–T cycles as well. As can be seen from Figs. 8 and 9, which are related to T-32 and T-A-32 respectively, the surface of T-32 deteriorated more than the surface of T-A-32.

3.2.5. Spacing factor analysis

To measure the air content percentage and air void distribution of the specimens, in order to support the durability results stated above, the vertical profile of each 150 mm × 300 mm cylindrical specimen was provided and scanned, and then the distribution and percentage of the air voids were measured by Bubble Counter Software, according to ASTM C457-12 guidelines (ASTM C457, 2012). The test was performed on three samples for each mixture design. Figs. 10 and 11 present the scanned figures of the profiles of T-32 and T-A-32, respectively. A lower spacing factor value means a shorter distance between air voids, which limits the distance that water must flow before reaching a void, thus allowing water to expand and freeze without causing perceptible damage. According to ASTM C-457 (ASTM C457, 2012), the air content (A) in % and the distribution of air voids known as the spacing factor (SF) can be

Fig. 8. T-32 without the air-entraining agent after 50 F–T cycles.

Fig. 9. T-A-32 with the air-entraining agent after 50 F–T cycles.

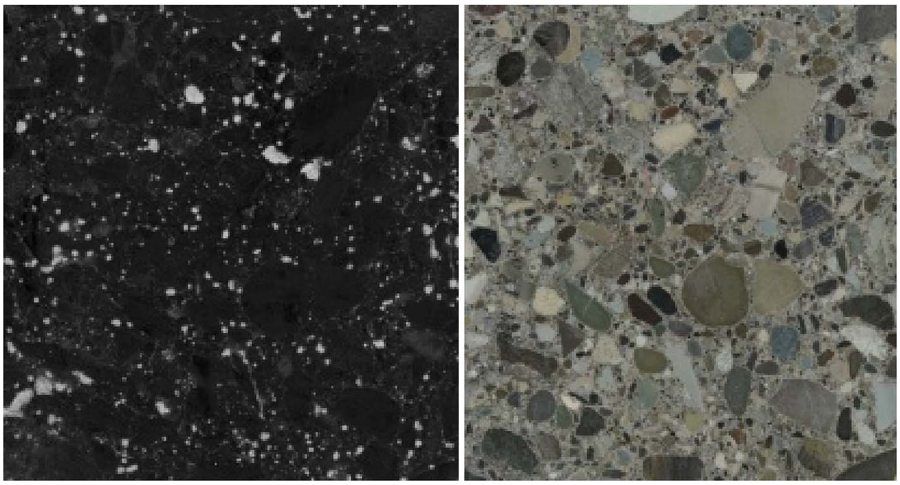


Fig. 10. T-32 without the air-entraining agent.

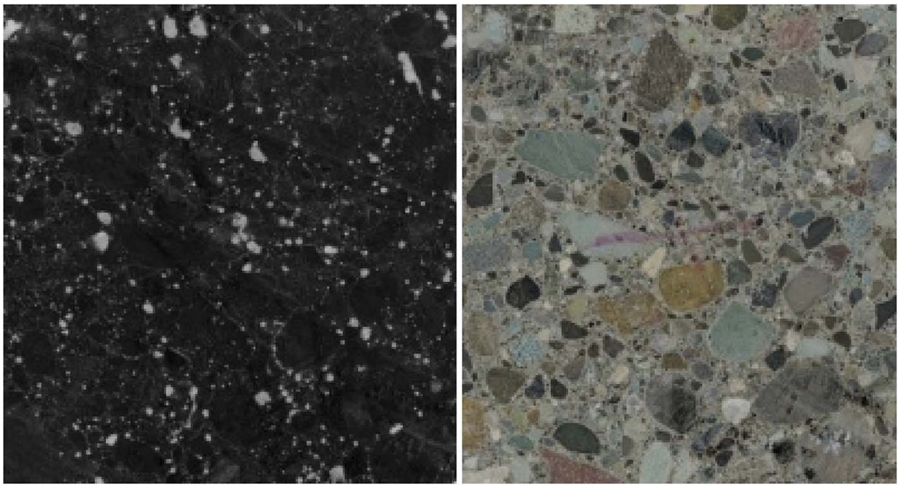


Fig. 11. T-A-32 with the air-entraining agent.

obtained as follows:

$$A = \frac{T_a \cdot 100}{T_t} \quad (2)$$

$$SF = \frac{T_p}{4N} \quad (3)$$

where T_a is the traverse length through the air void, T_t is the total length of the traverse, T_p is the traverse length through the paste, and N is the total number of air voids that are intersected. An SF value under 0.2 mm could be sufficient for concrete durability [38] (ASTM C672, 2003).

According to the SF values provided in Table 4, T-32 has an SF value similar to T-A-32, which could be due to the filling effect of pozzolans on the distribution of the air voids. That is, Trass has not altered the air void structure significantly. On the other hand, using the air-entraining agent decreases the SF value. The SF value for T-32 is 32% higher than that of R-32, however, this value for T-A-32 is 0.151 mm, which is 40% higher than that of R-A-32. This could be due to the heterogeneity of the specimens made with Trass, which makes the concrete structure develop more tortuous paths. These tortuous paths are suitable for larger volume of water to be absorbed into the concrete pore structure, and more voids may have been clustered compared to an ordinary concrete. In other words, it can be concluded that Trass has not led the air voids to be distributed homogeneously.

4. Conclusions

In this study the effect of Trass natural pozzolan and an air-entraining agent on mechanical and durability properties of roller compacted concrete was investigated. Having conducted extensive laboratory research, the following conclusions are drawn:

- The value of the VeBe test when using Trass is higher than that of plain concrete, and consequently, by using Trass, an extra amount of superplasticizer is needed to create a similar VeBe value. When using an air-entraining agent, the VeBe value is 10% lower than that of the specimen which contains Trass and does not contain the air-entraining agent.
- The compressive strength of the specimens containing Trass is 35% lower than that of the plain concrete at early ages, which could be due to the low pozzolanic activity of Trass that may not participate in hydration at early ages. Gradually, at the age of 90 days, the compressive strength of the specimens containing Trass is relatively improved, which indicates that Trass has compensated its lag in the production of C–S–H gel.
- Results signify that the tensile strength of the specimens containing Trass is 12% lower than that of plain concrete. Additionally, the air-entraining agent decreased both the compressive and tensile strengths.

Table 4
Spacing factor and air void percentage.

Sample ID	Spacing factor (mm)	Air content (%)
R-32	0.103	2.9
R-A-32	0.074	4.9
T-32	0.186	3.2
T-A-32	0.151	5.5

- At the age of 90 days, the specimens with natural pozzolan have a 10.8 mm water penetration depth, which is 14% lower than that of plain concrete. Dilution effect and low pozzolanic activity of Trass are responsible for the higher permeability at early ages. Moreover, when the air-entraining agent is used, the water penetration depths for both types of mixtures are decreased.
- The sorptivity coefficient for the specimens containing natural pozzolan is lower than that of plain concrete, which signifies capillary porosity reduction and loss of connectivity in the pore structure. The sorptivity coefficient of the specimens containing both Trass and the air-entraining agent is lower than that of plain concrete. This could be due to Trass natural pozzolan's capability to reduce the capillary porosity and conductivity of the pores.
- The mass loss value for the specimens containing pozzolan, when exposed to a deicer salt solution, is 51% higher than that of plain concrete. This is likely due to the lower reaction rate of Trass compared with cement. In fact, using Trass leads to the creation of clustered air voids which accordingly creates more F–T and salt scaling mass loss values; therefore, as the compressive strength has not been improved while using Trass, the mass loss value in the F–T cycles has not been reduced either, although the overall permeability has improved.
- The scaling factor value for the specimens containing both Trass and the air-entraining agent is 40% higher than that of plain concrete containing the air-entraining agent. This could be due to the heterogeneity of the specimens made with Trass, which makes the concrete structure develop more tortuous paths, suitable for a larger volume of water to be absorbed into, and more voids may have been clustered compared to an ordinary concrete.

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