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Case study

The effect of using low fines content sand on the fresh and hardened properties of roller-compacted concrete pavement

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ABSTRACT

Aggregate gradation is one of the most important property that influence the behaviour of roller-compacted concrete pavement (RCCP). There are some limitations for gradation of coarse and fine aggregates from the standards. Based on the ACI 211.3R, the content of sand size less than 75 μm should be between 2 to 8% of the total aggregates. To study the effectiveness of using a nonstandard sand (a sand with a gradation out of the specified restrictions) on the properties of RCCP, three types of sand with a difference in very fine particles content were used. The sands used are: 1) standard sand, 2) modified sands containing about 6% limestone powder, and 3) a low fines content sand containing <1% very fine particles. Two types of RCCP containing 12 and 15% cement were used as control mix. The results show that using low fines content sand or limestone modified sand instead of standard sand in RCCP increased Vebe time. The use of low fines content sand in RCCP did not have significant effect on the compressive, splitting tensile and flexural tensile strengths. However, the use of limestone modified sand in the RCCP significantly reduced the mechanical properties. RCCP was made of low fines content sand had more porosity than RCCP with standard sand. It can be concluded from test results that sand with lack in very fine particles can be used in RCCP.

1. Introduction

Roller compacted concrete pavement (RCCP) gradually has been considered as an attractive alternative to conventional road construction due to it is relatively easier to produce and more economical [1]. RCCP is a kind of rigid pavement which needs low water and low cement. RCCP is a zero slump concrete, therefore, it needs to obtain vibration liquefaction by vibration compaction construction technology [2]. RCCP has the same ingredients; aggregates, cementitious materials and water, but different ratios, as normal vibrated concrete. RCCP usually contains more aggregate (75 to 85 percent by volume) and less paste in comparison with conventional concrete [3]. The fresh properties and hardened strength of concrete are strongly influenced by aggregates [4,5]. Also, the most efficient way to achieve workable and high strength RCCP is by providing a well-graded aggregate [1,3,6]. For many applications such as soils, base and asphalt have demonstrated that the best performance is derived from blend of equidimensional particles that are well-graded from coarsest to finest [7].

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Aggregate gradation affect the compactability of RCCP and influence the number of vibrating required for full compaction [3]. Well-graded aggregates should be used in RCCP to minimize void space, optimize paste content, and provide a dense, smooth and tight surface [3,6].

Researches [6–9] highlighted that nominal maximum size of coarse aggregate has important role in fresh properties and hardened strength of RCCP. Portland Cement Association (PCA) and American Concrete Institute (ACI) have limited the percentage of fine aggregate passing through sieve #200 (0.075 mm) to 2–8% and sieve #100 (0.150 mm) to 6–18% for sand used in RCCP. In practice, providing standard sand containing such fines particles is difficult and time consuming. Modification of existing sand also is costly. LaHucik and Roesler [10] investigated nine RCCP mixture gradations with three primary aggregate sources available, which had low fines content, i.e., percent passing the 75 μm (#200) sieve. The cement content was fixed about 282 kg/m^3 for all nine RCCPs. These results were then compared to the strengths of a conventional concrete pavement mixture. The results demonstrated that RCCPs can achieve similar and even greater compressive strengths than a conventional concrete paving mix despite low aggregate fines content. A review on literature showed that there is not detail information regarding to effect of fine particles (passing through sieve #200 and #100) on the fresh properties and hardened strength of RCCP. Therefore, in this study, influence of using low fines content sand in mix proportions of RCCP was investigated. For this purpose, in a RCCP containing standard sand, the total standard sand was replaced with low fines content sand. The influence of this substitution on the Vebe time and hardened strengths was investigated. In addition, water absorption, porosity and ultrasonic pulse velocity tests were applied for the durability evaluation. Furthermore, Scanning Electron Microscope (SEM) was applied to assess microstructure of specimens.

2. Experimental program

2.1. Materials

The ordinary Portland cement (Type I), which conforms to MS522, part-1:2003 with a 28-day compressive strength of 48 MPa was used. Many of the RCCP constructed to date have been constructed using Type I or II Portland cement [6]. Local mining sand (low fines content sand) with fineness modulus and saturated-surface-dry specific gravity of 2.9 and 2.55 was used. It should be noted that the fineness modulus of standard sand was around 2.76. Grading of low fines content sand is shown in Fig. 1. Maximum nominal size, SSD specific gravity and 24 h water absorption of used coarse aggregate was 19 mm, 2.62 and of 0.67%, respectively.

It is reported that Lime stone powder (LSP) has filling effect and active effect and also accelerating effect during hydration process under the condition of high temperature steam curing [11,12]. LSP has not pozzolanic activity; it is still unhydrated at the age of 28 days [13]. However, the beneficial influences of LSP due to its filling effect on the fresh properties and hardened strengths of concrete have been reported [14–17]. In this study the filling effect of LSP was considered. The major content of LSP particle size passes from sieve #100 and #200 that provides good particle size distribution with low fines content sand. The particle size distribution of LSP is presented in Fig. 2. The gradation of standard sand, low fines content sand and limestone modified sand are shown and compared with PCA standard limitation in Table 1. As can be seen, the values for low fines content sand are lower than standard for sieves #8, #50, #100 and #200. However, those values for low fines content sand+6% LSP are comparable with standard sand.

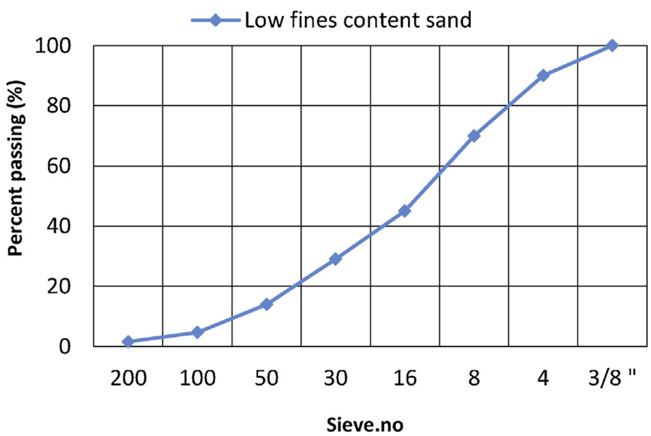

Fig. 1. Sieve analysis for low fines content sand.

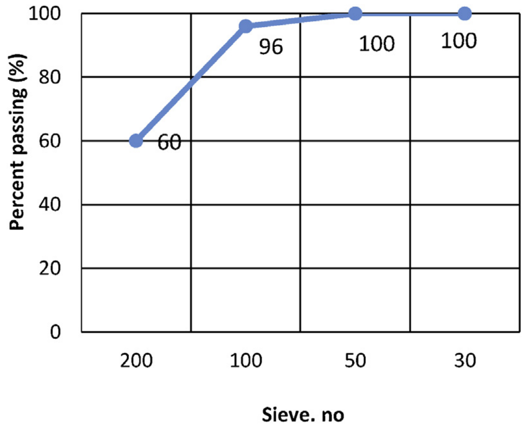

Fig. 2. Sieve analysis of Lime Stone Powder (LSP).

Table 1
Sieve analysis of aggregates in comparison with PCA standard limits.

Sieve No	PCA standard limits- Upper limit	PCA standard limits- Lower limit	Percent passing for standard sand	Percent passing for low fines content sand	Percent passing for low fines content sand+6% LSP
3/4 (19 mm)	100	90	100	100	100
1/2 (12.7 mm)	90	70	75.5	75	76.5
3/8 (9.5 mm)	85	60	65.7	65.25	67.34
#4 (4.75 mm)	65	40	45	41	44.51
#8 (2.36 mm)	50	29	36.3	33.6	37.61
#16 (1.18 mm)	40	20	27.2	23.41	28.04
#30 (0.600 mm)	30	14	20.1	15.26	20.39
#50 (0.300 mm)	23	10	14	8	13.57
#100 (0.150 mm)	18	6	8.3	2.5	8.17
#200 (0.075 mm)	8	2	4.21	0.7	4.32

2.2. Mix design and mixing procedure

Two groups of RCCPs containing 12% and 15% OPC by weight of total dry solids were used. The cementitious materials in RCCP is usually ranging from 12% to 16% of the total weight of dry materials [6]. For each cement content three groups of aggregates containing 1) well graded coarse aggregate + standard sand, 2) well-graded coarse aggregate + low fines content sand and 3) well-graded coarse aggregate + low fines content sand + 6% LSP were used. The mix proportions of all RCCPs are given in Table 2. In this table, ‘A-12’ and ‘A-15’ stand for “RCCPs with 12% cement” and “RCCPs with 15% cement”, respectively. Also, ‘SS’, ‘LFS’ and ‘LMS’ stand for “standard sand”, “low fines content sand” and “limestone modified sand”, respectively. Water to cement ratio for all mixes except mixes containing LSP is fixed to 0.40. LSP is very fine and significantly increases surface area of aggregate when it is used in concrete mixture. Therefore, the water content increased for RCCP containing LSP to get a satisfactory workability.

According to ASTM C 1435 [18] an electric vibrating hammer with a minimum power input of 900 W and be capable of providing at least 2000 impacts/min was used for freshly-mixed concretes compaction. Flexural tensile strength was determined using a prism mold. The preparation of the prism specimens was made using the same vibrating hammer

Table 2
Mixture proportions for RCCP and Vebe time.

Sample ID	Cement		LSP		Ratio of water to Cement	Aggregate (Kg/m^3)			Water (Kg/m^3)	Vebe Time (S)
	Kg/m^3	%	Kg/m^3	%		Coarse	Fine	Coarse to Fine ratio		
A-12-SS	269	12	–		0.40	1076	897	1.2	108	30
A-12-LFS			–		0.40					32
A-12-LMS			118	6*	0.47				127	34
A-15-SS	332	15	–		0.40	1028	857	1.2	133	26
A-15-LFS			–		0.40					27
A-15-LMS			113	6*	0.43				143	29

* 6% LSP is added to RCCP mixture by weight of total aggregate.

equipped with a shaft and rectangular plate. The cylindrical molds and prism specimens were cast in three layers, and each layer was fully compacted until mortar was formed on the top surface.

2.3. Test methods

Vebe time test was employed to assess the workability of RCCPs [19] by using a vibrating table and a surcharge in accordance with ASTM C1170 [20]. Compressive strength and splitting tensile strength tests were done according to ASTM C39 [21] and ASTM C 496 [22], respectively, at 1, 7 and 28 days on 100 mm × 200 mm cylindrical specimens. Also, the flexural strength test performed on 100 mm × 100 mm × 500 mm prism specimens according to the relevant standards ASTM C78 [23]. Water absorption values were measured according to ASTM C642 [24]. The water absorption test was conducted on 100 × 200 mm cylinder. Porosity test method that involves air evaporation from oven dried samples [25]. In this way, after evaporation of air from the oven dried samples, the water fills the pores under vacuum to reach full saturation. This method has been proposed by many other researchers [26]. The microstructure of specimens was considered by SEM test. The size of samples for this test was approximately 20 mm × 20 mm × 8 mm. Ultrasonic Pulse Velocity (UPV) test is an interesting non-destructive method that checks the quality, homogeneity and compressive strength of concrete [27,28]. In this study direct transmission was considered for ultrasonic measurement [29]. The UPV test was carried out on 100 mm cubes according to BIS 13,311 (Part 1)-1992. In this test, the frequency of the transducer was 54 kHz. It should be noted that three samples were prepared for each test. All samples were removed from the mold after 24 h and allowed to cure for 28 days. The foam ice box was prepared as a calorimeter to measure the heat capacity (C-value) of samples. Water as the material with known C-value was selected and the changing temperature between water and samples was monitored in isolated calorimeter. The C-value of samples was calculated based on the mass, and initial and equal temperature of water and specimens.

3. Results and discussion

3.1. Vebe time

Table 2 shows the vebe time for RCCPs. Based on the visual observation during mixing, placing and compaction; there was no segregation for all mixes. In addition, sufficient workability for all mixes was observed. As can be seen in Fig. 3 (surface texture at the time of Vebe test), RCCPs with standard sand and modified sand had a tight texture surface in comparison with RCCPs containing low fines content sand. This is due to the lack on very fine aggregate (aggregate passing though the sieve #100 and #200). Kosmatka et al. [30] reported that the amounts of fine aggregate passing sieve #50 and #100 influence the workability, surface texture, air content, and bleeding of concrete.

The Vebe time for RCCPs containing 12% and 15% cement was in the range of 30–34 sec and 26–29 sec, respectively. Vebe time for RCCP has been reported between 30 and 40 s, by ACI 325 [31]. However, Gauthier and Marchand [32] reported that Vebe time for RCCP should be between 40 and 90 s. The results showed that increasing cement from 12% to 15% for RCCPs

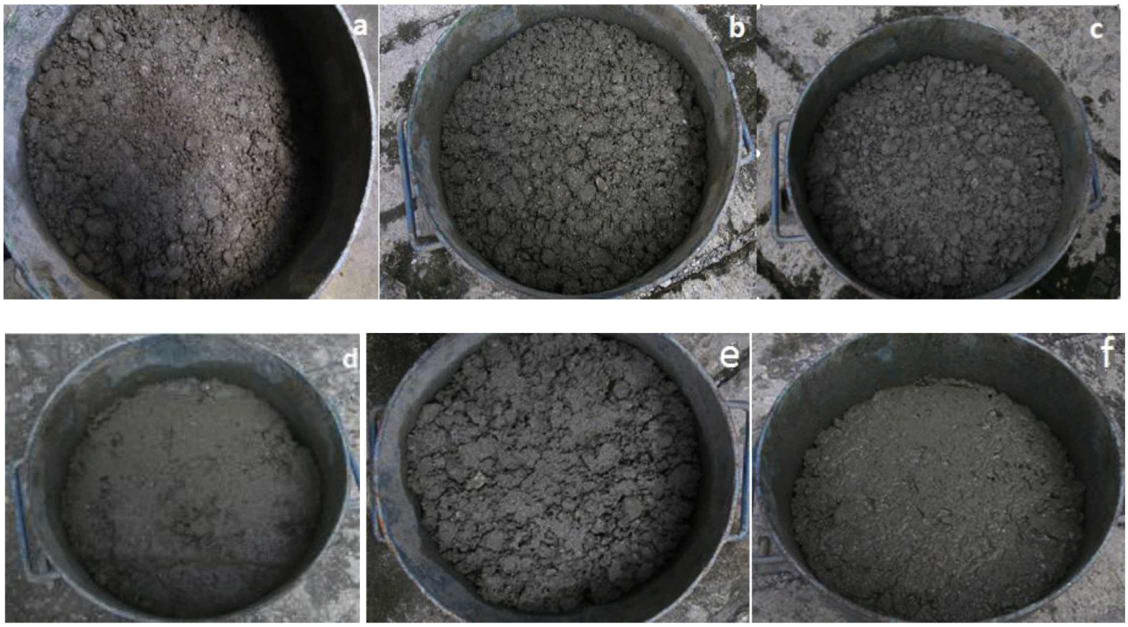

Fig. 3. Surface texture in Vebe time test. a: A-12-SS; b: A-12-LFS; c: A-12-LMS; d: B-15-SS; e: B-15-LFS; f: B-15-LMS.

containing standard sand, low fines content sand and modified sand decreased Vebe time by 13.3%, 15.62% and 14.70%, respectively. It shows in the absence of sufficient very fine particles passing from sieve #100 and #200, the role of cement to decrease Vebe time is important. Increasing cement content from 12% to 15% led to paste increment in concrete which is coating the surface of aggregates for easier consolidation and a better finish. The workability of RCCP is most influenced by the paste portion of RCCP mixture [33]. Less paste in the mixture reduces the workability of RCCP and may increase the risk of segregation [6]. Vahedifard et al. [34] showed that the cement increment from 12% to 15% in RCCP can decrease the Vebe time by 10 percent. On the other hand, RCCPs containing low fines content sand and modified sand increased Vebe time by 6.6%, 13.3%, respectively, in comparison with RCCP with standard sand at 12% cement content. Also, for RCCPs with 15% cement containing low fines content sand and modified sand increased Vebe time by 3.8%, 11.5%, respectively. It shows that the significant increases of Vebe time due to addition of 6% LSP.

3.2. Density

Table 3 presents and compares the oven dry density values of RCCPs containing standard sand, low fines content sand and modified sand. The oven dry density of RCCPs containing standard sand and low fines content sand were comparable. The oven dry density values of RCCPs with 12% and 15% cement containing standard sand and low fines content sand were in the range of 2364-2356 kg/m^3 and 2399-2383 kg/m^3, respectively. Generally, the density of the RCCP ranged from 2340 to 2510 kg/m^3 [6]. However, the oven dry density values of RCCPs with 12% and 15% cement containing modified sand decreased; in the range of 2301–2344 kg/m^3 and 2302–2368 kg/m^3, respectively. It can be concluded that higher W/C ratio leads to lower density due to air voids increment in concrete. It has been reported that an increment of 1% in the concrete porosity reduces the compressive strength about 3–5 MPa [35]. Varma reported that as W/C ratio increases from 0.5 to 0.6 the 28-day dry density decreased by 6% [36].

3.3. Compressive strength

Fig. 4 shows the compressive strength results of RCCP mixes containing different types of sand and cement content at different ages, with a standard deviation of 3% to 7%. As can be seen, RCCPs containing 12% cement with standard sand and low fines content sand have the approximately same compressive strength of 21 MPa and 29 MPa at 1 and 7days, respectively. However, slight reduction of about 3% was observed in RCCP mix with low fines content sand at 28-day. The same behavior was observed in RCCPs with 15% cement content. In 15% cement content, the compressive strength of RCCPs containing standard and low fines content sands were comparable at early ages of 1 and 7 days, while the use of low fines content sand caused 4% reduction on the 28-day compressive strength. These results present that the use of low fines content sand in RCCP, does not affect the compressive strength significantly. In addition, the results revealed that without the specified percent sand passing from sieve #100 and #200, the suitable packing density can be obtained due to heavy

Table 3
The 28-day oven dry density for RCCPs.

Sample ID	28- day oven dry density
A-12-SS	2364
A-12-LFS	2356
A-12-LMS	2301
A-15-SS	2399
A-15-LFS	2383
A-15-LMS	2344

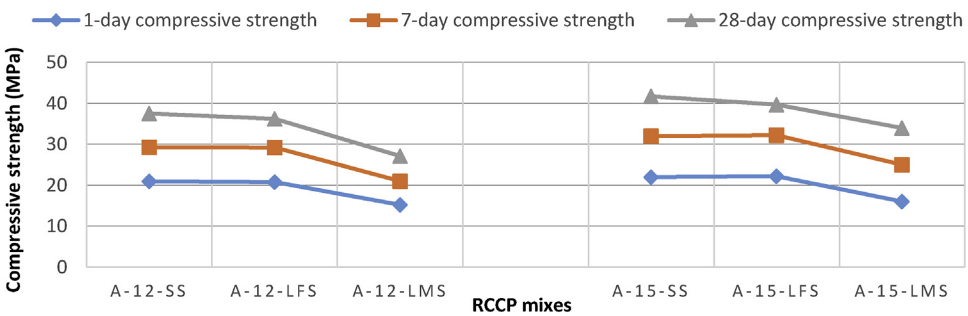

Fig. 4. Results of compressive strength for RCCPs with 12% and 15% cement.

compaction that must be applied for RCCP placement. In other words, the fine voids which is due to a lack of sand passing from sieve #100 and #200 could be removed largely because of heavy compaction in RCCP placement.

RCCPs containing modified sand with LSP showed the lowest compressive strength at all ages compared to RCCPs containing standard and low fines content sands. Although, by adding LSP to low fines content sand the gradation of sand was modified, however, the compressive strength for RCCP containing this sand significantly reduced at all ages. The reduction on the compressive strength for RCCP with modified sand decreased about 27%, 28% and 28% for 12% cement and 27%, 21% and 18% for 15% cement at 1,7 and 28 day ages, respectively, in comparison with RCCPs containing standard sand. The reduction of the compressive strength was due to higher mixing water in RCCP containing LSP. RCCPs containing 12% and 15% cement required 18% and 8% more water, respectively, to achieve a compactable fresh RCCP when LSP incorporated in the concrete mixture. As can be seen in these results, RCCP containing 15% cement needs less addition water, and, therefore, reduction of the compressive strength at 7 and 28-day ages was less than RCCP containing 12% cement. It can be concluded that RCCP is a kind of concrete which its compressive strength is highly affected with mixing water.

The cement increment from 12% to 15% significantly improved the compressive strength of RCCP with modified sand at 7 and 28 days. Increasing the 1, 7 and 28-day compressive strength for this RCCP was about 5%, 19% and 26%, respectively. While, the increment for RCCPs with standard sand and low fines content sands was almost the same of 5%, 10% and 11%, respectively. These results show that when a material with high surface area (LSP in this study) is used in RCCP mixture, increasing the cement content is necessary to improve its rheological properties of fresh state and compensate reduction of the compressive strength at the service time. However, based on test results of compressive strength the use of LSP to modify low fines content sand is not necessary. In accordance with ASTM C 330-05 [37] the 28-day cylinder compressive strength should be more than 17 MPa. It is noticeable that the compressive strength increment was highly influenced by curing time in comparison with cement increment. For instance, the compressive strength of RCCPs containing 12% cement with standard sand, low fines content sand and modified sand increased by 39, 40 and 38% within 7-day curing period, and 28, 25 and 29% within 28-day curing time, respectively.

3.4. Splitting tensile strength

The splitting tensile strength results for all RCCPs at the ages of 1, 7 and 28 days are shown in Fig. 5, with a standard deviation of 4%–10%. Test results show that the splitting tensile strength of two RCCPs containing standard sand and low fines content sand are almost the same at all ages in both cement contents. This show that existing very fine particles (sands passing through sieve #100 and #200) in the sand used in RCCP is not critical.

Although, LSP modified the grading of low fines content sand, however, there was a considerable reduction of splitting tensile strength for both groups of RCCPs at all ages. The splitting tensile strength decreased about 29%, 25% and 23% for RCCP with 12% cement and 23%, 16%, 15% for RCCP with 15% cement at 1, 7 and 28 days, respectively, in comparison with RCCP containing standard-sand. It shows that the splitting tensile strength decline has been decreased slightly with further cement hydration by 28-day curing ages. So, completion of cement hydration for RCCP containing LSP can provide stronger structure.

On the other side, the cement increment from 12% to 15% increased splitting tensile strength at all ages. Increasing cement from 12% to 15% for RCCPs containing standard sand, low fines content sand and modified sand raised the splitting tensile strength about 7%, 10% and 19% at 28 days, respectively. As same as compressive strength, the cement increment was more useful for RCCP with modified sand. In addition, increasing cement from 12% to 15% raised the splitting tensile strength of RCCP with low fines content sand more than RCCP containing standard sand. This may be due to exception of sufficient fine particles passing the sieve #100 and #200 in RCCP with low fines content sand. The minimum splitting tensile strength of 1.85 MPa for concrete which is used in road construction is determined by British Department of Transport [38]. Thus, all RCCPs containing standard-sand, low fines content sand and modified sand could be used for road construction.

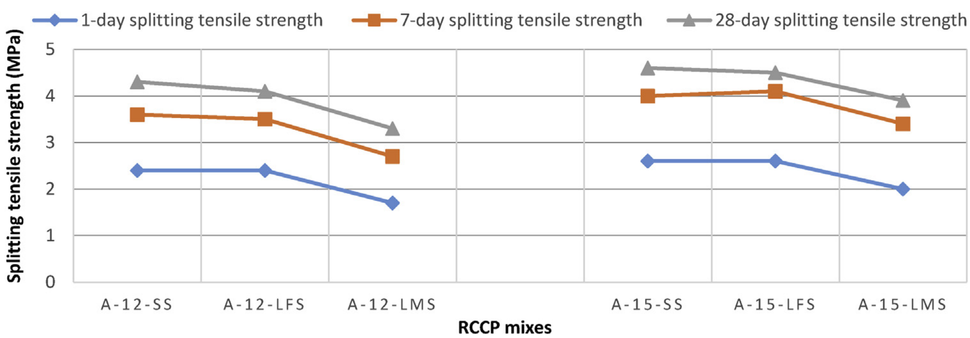

Fig. 5. Results of splitting tensile strength for RCCPs with 12% and 15% cement.

3.5. Flexural tensile strength

The pavement usually is designed on the basis of flexural tensile strength [7]. However, opening the pavement to traffic may be on the basis of compressive strength. The flexural tensile strength results are shown in Fig. 6 with a standard deviation of 4%–10%. The flexural tensile strength results for RCCPs with 12% cement containing standard sand and low fines content sand was comparable at all ages. Also the same behavior was seen for RCCPs with 15% cement content. It means that the low fines content sand does not have negative effect on flexural tensile strength at all ages. However, there was a significant reduction for flexural tensile strength of RCCPs containing modified sand at all ages. A decrease in the water to cement ratio is generally commensurate with increase in the compressive and flexural strength [9]. The flexural strength for RCCPs with 12% and 15% cement containing modified sand decreased about 38% and 27% at 1 day, 35% and 13% at 7 days, 31% and 11% at 28 days, respectively. It shows that the reduction for flexural strength of RCCPs with 15% cement containing modified sand was lower than RCCPs containing 12% cement at all ages.

Increasing cement from 12% to 15% increased also the flexural tensile strength of RCCPs at all ages. The highest increase for flexural tensile strength due to cement increment for RCCPs containing standard sand, low fines content sand and modified sand was observed at 7 days about 14%, 17% and 51%, respectively. However, it was not significant at 28-day curing ages for RCCPs containing standard and low fines content sands; in average of 8%. It should be noted that the role of cement increment was more considerable for RCCPs included limestone modified sand at all ages. Also, increasing cement from 12% to 15% was more useful for low fines content sand in comparison with standard sand. A minimum allowable flexural strength of 4.13 MPa at 28 days for airport pavements is determined by Federal Aviation Administration (FAA) [7]. Also, the flexural strength of 4.0 MPa at 28 days is restricted by British Airport Authority (BAA) [39]. Thus, all RCCPs except A-12-3 can be used for airport pavements.

3.6. Water absorption

Water absorption of concrete is fluid flow in porosities of unsaturated concrete specimens when there is not any external pressure on the specimens [40]. Water absorption usually uses as an important factor for quantifying the durability of cementitious systems [41]. CEB [42] divided concrete into good concrete with water absorption < 3%, average with water absorption 3–5% and poor concrete with water absorption > 5%. The results for initial water absorption after 30 min and final water absorption after 72 h are demonstrated in Fig. 7. The initial surface water absorption of RCCPs showed values lower than 3%, except A-12-LMS that indicated 4.5%. In addition, the final water absorption for RCCPs with 12% and 15% cement

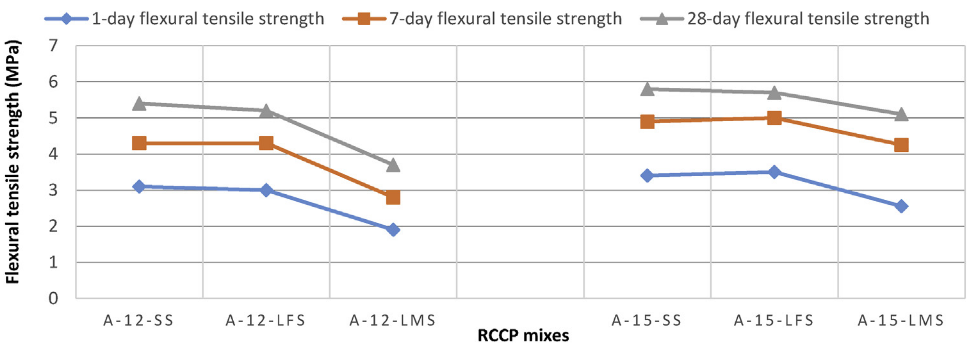

Fig. 6. Results of flexural tensile strength for RCCPs with 12% and 15% cement.

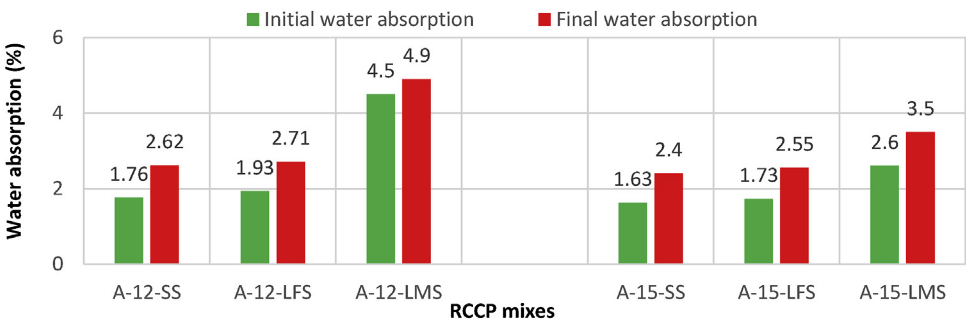

Fig. 7. Initial and final water absorptions of the RCCPs.

containing standard sand and low fines content sand was lower than 3%. However, it was 4.9% and 3.5% for RCCPs containing 12% and 15% cement including limestone modified sand, respectively. The final water absorption for RCCPs with 12% and 15% cement included modified sand increased by 87% and 45% in comparison with RCCP containing standard sand, respectively, while final water absorption values were comparable for RCCPs with standard sand and low fines content sand.

Increasing cement from 12% to 15% decreased the initial water absorption for RCCPs containing standard sand, low fines content sand and modified sand in average of 7%, 10% and 42%, respectively. Also the final water absorption decreased about 8%, 6% and 28% for RCCPs containing standard sand, low fines content sand and modified sand, respectively.

The initial and final water absorption results for RCCP specimens revealed that 1) the low fines content sand which is not included sufficient dust fraction (sand passing the sieve #100 and #200) did not affect the initial and final water absorption of RCCP specimens significantly at both cement contents. 2) LSP increased the initial surface and final water absorption due to demand more mixing water which provides more air voids and capillary voids in cement paste. 3) increasing cement from 12% to 15% can slightly affect the initial surface and final water absorption of RCCPs containing standard sand and low fines content sand, while those values for RCCPs containing modified sand were influenced strongly.

3.7. Porosity

Calculating the total volume of capillary voids in Portland cement pastes, popularly known as porosity [9]. Porosity may significantly affect the strength of concrete. There is an inverse relationship between strength of solids and porosity [43]. Porosity is an important parameter which affect the hardened strengths and durability of concrete [25]. The porosity and pore size distribution of cement based materials significantly affect their mechanical and durability properties [44].

Porosity results of the RCCPs is presented in Fig. 8. It can be seen that the porosity of RCCPs with 12% cement containing low fines content sand and modified sand increased by 12% and 100% in comparison with RCCP containing standard sand. Also, the porosity for RCCPs with 15% cement containing low fines content sand and modified sand raised by 7% and 33%. It could be concluded that the porosity of RCCP can be influenced slightly by low fines content sand. However, the limestone modified sand affected the porosity of RCCP strongly that is resulted from higher mixing water. The increase in total porosity is due to increase in water to cement ratios [9]. Decreasing porosity in RCCP provides high-strength and durable concrete [45]. However, increasing porosity allows the penetration of air and water, and reduces the durability of concrete [6].

As such as water absorption of RCCP specimens, increasing cement from 12% to 15% decreased porosity values about 2%, 6% and 35% for RCCPs containing standard sand, low fines content sand and modified sand, respectively. However, this reduction for standard sand and low fines content sand RCCPs was not considerable, while it was a significant decline for RCCP containing modified sand.

The relationship between 28-day compressive strength and porosity for RCCPs with 12% and 15% cement containing standard sand and low fines content sand is presented in Fig. 9 The figure shows a good correlation between 28-day compressive strength and porosity for all RCCPs.

3.8. Scanning Electron Microscope (SEM) Test

The hydrated cement paste is included different types of voids. These voids significantly influence hydrated cement paste properties. Entrapped air voids could be as large as 3 mm, however, entrained air voids mostly range from 50 to 200 μm [9]. The SEM images of RCCPs containing standard sand, low fines content sand and modified sand are shown in Fig. 10. AS can be seen the RCCP specimens with 12% and 15% cement containing standard sand showed the average void size of 37 μm. Also, the average void size for 12% and 15% cement RCCPs containing low fines content sand and modified sand were about 61 μm and 147 μm, respectively. However, increasing cement from 12% to 15% influenced the void sizes especially RCCPs containing modified sand. The biggest voids size decreased from 52 to 43 μm for standard sand, from 90 to 78 μm for low fines content sand and 250 to 120 for modified sand when the cement content increased from 12% to 15%, respectively.

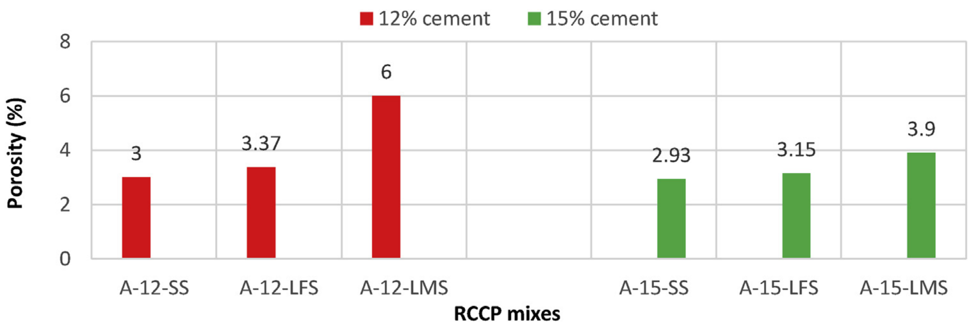

Fig. 8. Porosity for RCCPs containing 12% and 15% cement at 28-day ages.

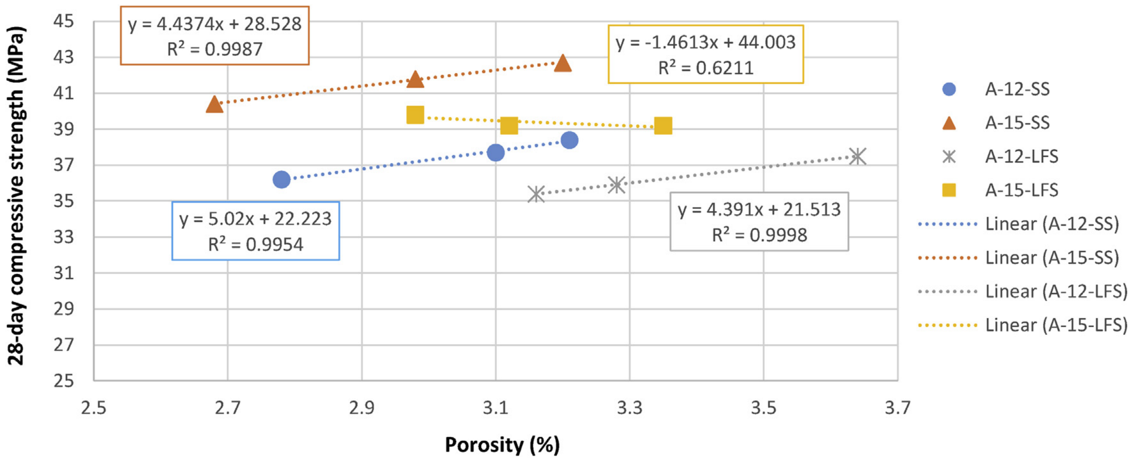

Fig. 9. Relationship between 28-day compressive strength and porosity.

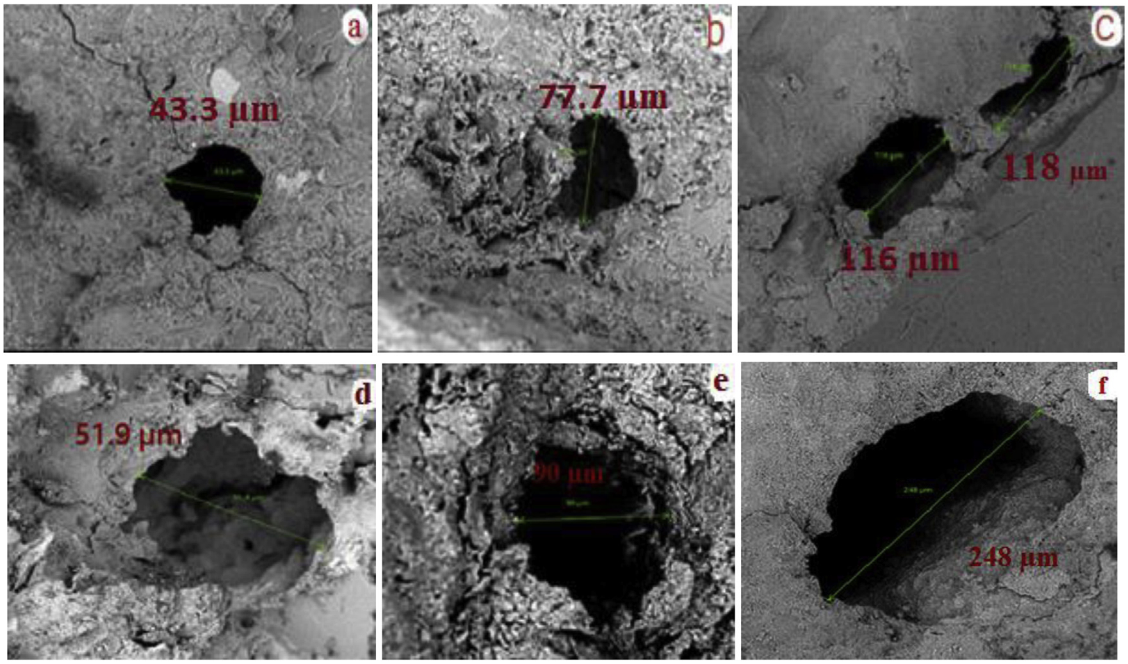

Fig. 10. Void sizes in the paste of RCCPs. a: A-15-SS; b: A-15-LFS; c: A-15-LMS; d: A-12-SS; e: A-12-LFS; e: A-12-LMS.

The SEM results has proven that 1) the dust fraction (sand passing the sieve #100 and #200) can affect the void sizes but not significantly. It means that the void sizes increment in the absence of dust fraction do not have a determinative role for fresh and hardened strength of RCCP 2) although increasing cement has a positive role for RCCP containing standard sand and low fines content sand but this effect is not considerable and it cannot be justified economically. However, cement increment was more useful for RCCP containing limestone modified sand 3) the void sizes could be influenced by mixing water strongly. The water to cement ratio, and the age of cement hydration significantly affect pore size distributions. Generally, permeability and compressive strength of concrete are affected by large pores, while the drying shrinkage and creep are usually affected by small pores [9].

3.9. Ultrasonic pulse velocity

Ultrasonic Pulse Velocity (UPV) tests are very sensitive to homogeneity and density variations and can provide important data for decision making about the conditions of concrete structures [46]. The range of UPV varies from 3 to 4.5 km/s (IS 13311) [29]. For excellent quality concrete, good quality concrete and medium quality concrete the UPV

Table 4
The specific heat capacity of RCCPs.

Sample ID	Specific heat capacity (kJ/kg °K)
A-12-SS	0.981
A-12-LFS	0.986
A-12-LMS	1.053
A-15-SS	1.007
A-15-LFS	1.018
A-15-LMS	1.097

must be more than 4.5 km/s, varying between 3.5–4.5 km/s and between 3.0–3.5 km/s, respectively. In this study, the UPV was about 4.72 and 4.61 km/s for RCCPs containing standard sand with 15% and 12% cement, respectively. Therefore, RCCPs with standard sand were in the range of excellent quality concrete. Also, this value for RCCPs containing low fines content sand with 15% and 12% cement was around 4.54 and 4.43 km/s, respectively. However, the UPV value for RCCPs containing modified sand with 15% and 12% cement decreased by 4.1 and 3.9 km/s, respectively. Ye et al [47] concluded that the mixes with lower w/c ratio had higher values of UPV, which could be associated with higher amount of solids in those mixes. The UPV is a function of the density of the concrete and it decreases with increasing porosity and permeability [48,49]. It can be concluded that due to slight difference between UPV values of standard sand and low fines content sand, uniformity, quality and density of RCCP may not be affected by low fines content sand significantly. In addition, increasing cement from 12% to 15% has a positive effect on the quality and providing dense structure in RCCP production.

3.10. Specific heat capacity (C-values)

Table 4 summarized the C-values of RCCPs containing standard sand, low fines content sand and modified sand. The specific heat capacity of concrete is dependent on the raw materials ingredient [50]. The C-value of cement, fine aggregate, coarse aggregate and LSP are 0.736 kJ/kg.°K, 0.734 kJ/kg.°K, 0.790 kJ/kg.°K and 0.837.4 kJ/kg.°K at room temperature, respectively. However, the C-value of air and water is around 1.005 kJ/kg.°K and 4.2 kJ/kg.°K, respectively.

Despite of the same raw materials, the C-value of RCCPs containing standard sand is less than RCCPs containing low fines content sand. It can be attributed to the higher porosity of RCCPs containing low fines content sand. The modified sand sample had the highest heat capacity due to higher porosity, higher W/C ratio and containing limestone powder. The samples should leave in room temperature for a while to receive to the equal room temperature for experiment test. This is why the pores might be filled with the humid air. The higher value of specific heat of RCCPs containing 15% cement in comparison with the samples containing 12% cement can be attributed to the higher amount of cement gel.

4. Conclusions

Based on the test results of this experimental work the following conclusions could be drawn:

1 The use of low fines content sand or modified sand in RCCP increased the Vebe time.
2 Low fines content sand did not affect the compressive strength of RCCPs containing 12% and 15% cement at early ages of 1- and 7-day. However, there was a slight reduction of about 3% and 4% on the 28-day compressive strength of RCCPs containing 12% and 15% cement contents, respectively.
3 Although, LSP modified the gradation of low fines content sand, however, RCCPs containing this modified sand showed the lowest compressive, splitting tensile and flexural tensile strengths in comparison with RCCPs containing standard sand and low fines content sand.
4 The use of low fines content sand instead of standard sand in RCCP did not significantly influence the porosity and water absorption values.
5 Scanning electron microscope images of RCCP specimens indicated that the void sizes slightly increased in absence of standard sand including very fine particles.
6 Although, the UPV test results for RCCP containing low fines content sand slightly decreased in comparison with standard sand, however, the results revealed that the use of low fines content sand may lead to tight and dense structure in RCCP.
7 The RCCPs containing low fines content sand or modified sand illustrated higher C-value in comparison with RCCP prepared with standard sand.

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Conflict of interest

None.

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