Investigation of external sulphate attacks and moisture effects on roller-compacted concrete pavement mixes containing micro silica sand powder

Zahraa Alaa M.A. Ali Khan¹ and Assist. Prof. Dr Zena K. Abbas²

¹, ² University of Baghdad, College of Engineering, Department of Civil Engineering, Baghdad, Iraq. Email: zahraa.alaa333@gmail.com

Abstract. External sulphate attacks (ESA) and water movement tend to produce the most deleterious effects on concrete. This study therefore aimed to investigate the durability of a roller compacted concrete (RCC) mix created with better engineering properties to be suitable for road paving. This RCC concrete has a dry consistency and low cementitious materials (cms) content. Slabs were prepared in dimensions of 380×380×100 mm by taking sulphate resistant Portland cement and replacing various proportions with silica sand powder (SSP) (5%, 10%, and 20%) on a weight-to-weight basis. Additionally, crushed stone, M-sand, filler, and water were added in appropriate proportions. The slabs were subjected to normal curing for 28 days, then sawed into prisms of 380×100×100 mm and cubes of 100×100×100 mm. Cyclic wetting at 23±2°C once in 5% MgSO₄ solution and then in water, followed by drying at 60°C for 30 and 60 cycles was then used to investigate the durability of the RCC specimens. Mixes with 5% SSP achieved the best results with increases of 5.46% and 35.24% for compressive (f’c) and flexural (fₚ) strengths, respectively, while absorption and volume of voids was decreased by 57.3% & 52.29%, respectively, after 60 cycles of MgSO₄ wetting and drying, as compared to the control mix.

1. Introduction
The term durability, when applied to concrete, signifies the resistance of the material to exposure to certain environmental conditions surrounding a given structure [1]. Sulphate attacks may be chemical in nature, occurring due to reactions between products, or physical, occurring during phase changes in sulphate solution intrusion [2]. The degree to which concrete is degraded is dependent on either case on many factors, such as the source of the sulphate ions, their type and concentration, and the permeability of the concrete itself [3], [4]. Water is one of the most destructive weathering elements for concrete structures, and it damages or destroys buildings and structures more frequently than any other natural disaster [5].

This study focuses on the durability of RCC mixes containing silica sand powder (SSP) with regard to both water effects and external sulphate exposure in order to examine the tendency of such concrete to suffer degradation over time. The intent is to produce RCC mixes suitable for road paving that offer better engineering properties in this regard.

Micro-filling and pozzolanic effects both result in pore refinement and porosity reduction, leading to a dense pore structure in both the bulk-paste matrix and transition zones of concrete. This contributes to increasing concrete resistance to corrosion [6]. The flexural strength (fₚ) of RCC sawed prisms of 100×100×380 mm, cured in water for 28 days then exposed to cyclic wetting and drying using water, cyclic wetting and drying in Na₂SO₄, and freezing and thawing were studied by...
This study observed that $fr$ was decreased for all exposure types and alternative exposure cycles. Additionally, the $fr$ increased both with increasing cement content and when sulphate resistant Portland cement (SRPC) and crushed aggregates were used. The researchers mentioned that the concrete resistance to sulphate attack decreased at higher surface water absorption rates, however. Similarly, there was a weak correlation between internal water absorption and resistance to sulphate attack [8].

The durability of mortar mixtures exposed to external and internal sulphate attacks was also studied by Arel and Thomas [9]. Standard curing was applied to mortar samples for 23 weeks, and at the end of a further 23 weeks of sulphate exposure, the compressive strength losses after exposure to external sulphate attacks from 7% Na$_2$SO$_4$ and from 8% MgSO$_4$ were found to be 43.1% and 48.9% respectively, while the flexural strength losses were found to be 57.8% and 67.1%, respectively.

Standard curing of 28 days was applied to cylindrical mortar samples of Φ50mm×L100mm and prismatic bars of 25mm×25mm×285mm, which were then subjected to four types of exposure for up to 270 days, including the use of Na$_2$SO$_4$ to examine sulphate exposure, with solutions refreshed every 2 months [10]. The compressive strength results from that study are presented in Figure 1.

The ultrasonic pulse velocity (UPV) behaviour in both plain and reinforced damaged concrete was evaluated in [11]. This evaluation also included plain concrete as a comparison, and three grades of target strength were studied, being 25, 35, and 45 MPa. Concrete cubes of 200×200×200 mm and reinforced beams of 100×150×1100 mm were used for this purpose. The study concluded that the UPV decreased with any increase in the level of damage for each strength grade, as shown in Figure 2.

![Figure 1](image1.png) **Figure 1.** The $f'_c$ of mortar after various exposure types [10].

![Figure 2](image2.png) **Figure 2.** Effect of the damage levels on UPV [11].

Another sulphate attack investigation also had specimens immersed in a 5% Na$_2$SO$_4$.10H$_2$O solution and subjected to cyclic wetting and drying. The researchers thus studied different properties for two concrete mixtures (C1 and C2) before exposure (T0) and after 1 and 2 months of exposure (T1 and T2, respectively). The porosity results are presented in Figures 3. a, b, and c. These show that the drying cycles induced and accelerated severe degradation based on the generation of expansive compounds in all concrete samples [12].
Cyclic wetting and drying has been repeatedly confirmed as a subsidiary factor in concrete deterioration, with the cyclic effect increasing diffusion and capillary absorption during the wetting period, while the drying period causes concrete shrinkage and results in micro-cracking [13],[14]. The effect of sulphate exposure on different mortar compositions (Portland cement (PC), PC + limestone filler (LF) and, PC + quartz filler (QF)) were studied by De Souza [15], using PC replaced to 10% by LF and QF, by weight. Tests were then made to evaluate the mixes’ properties of resistance against Na$_2$SO$_4$ and MgSO$_4$ attacks, with concentrations of 0.704 mol/l for both solutions. The results indicated that replacing the cement with quartz filler produced better sulphate resistance. Figures 4. a and b show the mechanical strengths obtained in that study.

The different properties of conventional concrete and RCCP mixes have also been studied. The UPV was one of these properties, studied using the direct method on cubes of 100 mm. The results showed that the UPV values were in the range 4.61 to 4.77 km/s for two selected RCC mixes, RCCP1 and RCCP2. Good correlation was also observed between UPV and $f’c$ at 28 days [16], as shown in Figure 5.
2. Experimental work

2.1. Materials

Crushed stone (CS) was brought from Al Nibaee region for use as coarse aggregate in this work; this has an NMAS of 19 mm and sulphur content (SO₃) of 0.056%. The specific gravity and absorption were 2.632 and 0.49%, respectively. Manufactured Sand (M-Sand) was used as fine aggregate in this work, from the same source as the CS with a sulphur content (SO₃= 0.309%). The specific gravity and absorption were 2.591 and 2.34%, respectively. The M-sand and CS aggregates also satisfied Iraqi specification IQS No. 45-84 (16) and ASTM C33/33M-18. The combined grading used in this work was selected to create dense gradation of type II (binder course) as defined by the State Commission for Roads and Bridges SCRB/R9-07, and as shown in Figure 6. Silica Sand Filler (SSF), a natural silica sand forming a white non-plastic material, was brought from the Al Anbar Governorate in the Urduma region of Iraq and used as a filler (100% passing a 0.075 mm sieve). The specific gravity and absorption were 2.6 and 0.4%, respectively. Iraqi Type V Portland cement of the Al JESR type was used for the RCC mixes, offering properties as shown in Table 1 that conformed with both IQS No. 5 and ASTM C150-15.

Table 1. Type V Portland cement properties

| Properties                  | Fineness Blane (m²/Kg) | C₃A%  | SO₃%  |
|-----------------------------|------------------------|-------|-------|
| Results                     | 357                    | 0.594 | 2.25  |
| IQS NO.5 Requirements       | 250 Min.               | 3.5 Max. | 2.5 Max. |
| ASTM C150 Requirements      | 280 Min.               | 5 Max. | 2.3 Max. |

The silica sand powder (SSP) (specific gravity =2.61) used in this work was obtained by the mechanical grinding of natural silica sand using an electrical mill; the base material was obtained from the same source as the SSF. The properties of this SSP met the requirements of ASTM C618-19, as presented in Table 2. Tap water was used for mixing and curing all concrete batches.

Table 2. Silica sand powder (SSP) results and requirements

| Properties | Retained% on Sieve | Water Table% | Strength | Activity Index | SiO₂% + | Fe₂O₃% + | SO₃ | Moisture content% | Loss on Ignition |
|------------|--------------------|--------------|----------|----------------|---------|----------|-----|-----------------|-----------------|
2.2. Proportioning

In terms of proportioning the RCC mixes, CS and M-Sand were used in percentages of 49% and 47%, respectively. A 4% fine (SSF) was used, and all aggregates were selected according to their gradation results. The cementitious materials were composed of type V Portland cement, replaced by different percentages (5%, 10%, and 20%) of SSP on a by-weight basis; these mixes were thus designated as M-SSP5, M-SSP10, and M-SSP20, with the control mix, M-R created with 0% SSP. ASTM D1557-12e1 method C was used for proportioning the RCC mixes, as suggested in [17] and [18]. Different moisture contents were also added (0.045, 0.05, 0.055, 0.065, 0.075, and 0.085), in order to identify the optimum water content (OMC%) to maximum dry density, $\gamma$ dry max. (gm/cm$^3$), for each mix [19]. The results of applying ASTM D1557-12e1 are shown in Figure 7, while Picture 1 shows the RCC dry mix constituents and Picture 2 shows one mix in a proctor mould.

![Picture 1. RCC dry mix elements.](image1.png)

![Picture 2. RCC mix in a proctor mould.](image2.png)

2.3. Moulds and Mixing
The mould used in this work for casting RCC slabs with handles for handling is shown in Figure 3. Before the RCC mix was added, the mould interior was wiped, and nylon sheets were used to prevent moisture and fine materials from mix seeping from the mould. The mixing method followed ASTM C192/C192M-19. Based on the proctor test results, the quantities of materials for each RCC mould of 0.014 m$^3$ for each mix were calculated as illustrated in Table 3.

**Table 3.** Material weights, and W/CMs ratios for 0.014 m$^3$ of RCC mould for various RCC mixes

| Mix-ID | Mix-Description          | Cement | SSP | M-sand | CS | Filler | w/cms |
|--------|--------------------------|--------|-----|--------|----|--------|-------|
| M-R    | RCC-0%SSP 100%Cement     | 4.62   | 0   | 13.5   | 13.95 | 1.14   | 0.38  |
| M-SSP5 | RCC-5%SSP 95%Cement      | 4.37   | 0.23| 13.41  | 13.86 | 1.13   | 0.39  |
| M-SSP10| RCC10%SSP 90%Cement      | 4.12   | 0.46| 13.35  | 13.8  | 1.13   | 0.4   |
| M-SSP20| RCC20%SSP 80%Cement      | 3.64   | 0.91| 13.27  | 13.71 | 1.12   | 0.42  |

2.4 Compaction

2.4.1. Vibrating table compaction. Each RCC mix was densified using a vibrating table, as shown in Figure 4. Each mix was placed in the mould as three layers, with each layer vibrated for 30s then levelled per ASTM C1170/C1170M-20. This vibration was intended to produce some initial compaction, as seen in the field [17].

![Picture 3. RCC mould.](image)

![Picture 4. RCC mould on a vibrating table.](image)

2.4.2. Manual compaction (hand-made roller device). For the final compaction, a roller device made in a local workshop was used, as shown in Figure 8. The procedure adopted by Abed and Salih [19] and Rahim et al. [20] was thus implemented. The compaction was made on plain ground, as shown in Figure 5, and a two-direction densification (x-x and y-y) process was executed to ensure uniformity. The three-part compaction procedure was thus completed as follows:

Part 1. Compaction using the weight of the device (38 kg), a static linear load of 1.1 kg/cm, and 14 to 16 passes.

Part 2. Compaction using weights (38 kg +74 kg =112 kg, added as burdens), placed in the steel box of the roller device, a static linear load of 3.2 kg/cm, and 10 to 12 passes.

Part 3. Compaction using weights (38 kg +74 kg + 74 kg =186 kg, added as burdens), a static linear load of 5.3 kg/cm, and 10 passes.

Inside dimensions (38×38×10) cm
2.5. Curing
Initial and final curing were done as recommended by ASTM C192/C192M-19 once rolling was completed. The moulds were protected against loss of moisture by layers of burlap (jute) cloth and nylon sheets and left at room temperature for 24 hrs for initial curing. Picture 6 shows a sample of RCC slab prepared for final curing. The final curing was done by immersing the RCC slab samples in a water receptacle at a temperature of 22° C for 28 days, as shown in Picture 7.

2.6. Sawing and Testing RCC specimens
To obtain the necessary RCC cubes and prisms, saw cutting was implemented according to ASTM C42/C42M-20. Forty-eight cured slabs of 38×38×10 cm were sawn into cubes of 10×10×10 cm and prisms of 38×10×10 cm. Each slab was thus sawn into three cubes and two prisms using a steel-diamond saw disk in two stages:
1. Cutting after 7-day curing for each RCC mix (M-R, M-SSP5, M-SSP10, and M-SSP20). Several slabs were sawed to determine whether suitable specimens could be obtained at this stage. Unfortunately, sawing at that age affected the samples negatively; immaturity of the RCC slab samples tended to lead to concrete disintegration, as shown in Picture 8, and the results could not be considered.

2. Cutting after 28-day curing. When the concrete had reached the required hardness, it was assumed to be able to sustain cutting, as shown in Picture 9. Each slab was thus sawn into three cubes and two prisms.

2.7. Exposure System
The exposure system adopted for this work was based on ASTM C88/C88M-18 and ASTM C1012/C1012M-18b, with some modifications to take previous work into account [9], [12], [7], [8], [21]. All concrete specimens were cured normally for 28 days, then subjected to various types of exposure. The specimens were each placed in a suitable plastic container with a lid that closed tightly to prevent evaporation or dilution of the solution or any contamination from outside sources. Picture 10 shows the stored specimens, while Picture 11 shows the oven-dried specimens. Table 4 illustrates the exposure types adopted for this work.
9

Picture 10. Stored specimens during immersion.

Picture 11. Specimens during the drying process.

Table 4. Exposure systems adopted in this work

| Type of Exposure                      | Exposure Conditions                                                                 |
|--------------------------------------|--------------------------------------------------------------------------------------|
| Wetting and drying in sulphate Solution | - Wetting (complete immersion) in a 5% MgSO$_4$ solution at a temperature of 23±2°C for 24 hrs; solution refreshed every 4 weeks. |
|                                      | - Drying in an oven at a temperature of 60°C for 24 hrs.                             |
| Wetting and drying in water          | As above, but in water only                                                          |

3. Testing

3.1. Compression Test
BS EN, 12390-3-19 was used to test the $f'$ of the 10×10×10 cm cubes after each exposure, as shown in Picture 12.

3.2. Flexural strength test
BS EN, 12390-5-19 was used to find the $fr$ of the 38×10×10 cm prisms after each exposure, as presented in Picture 13.
3.3. Pulse Velocity (UPV) test
A MATEST device was used to determine the UPV as per ASTM C597-16 for all specimens after each exposure, as shown in Picture 14.

3.4. Absorption%, Voids%, and Density Test
ASTM C642-13 was used to specify the percentages of absorption, permeable voids, and density for different RCC mixes in 10×10×10 cm cubes after each exposure, as shown in Picture 15.

4. Results and Discussion
Figure 9 a shows the $f'c$ results for all RCC cubes, indicating that the $f'c$ decreased as the number of exposure cycles (wetting and drying) increased. This could be due to the rapid re-crystallisation of hydrated products after the dissolution of anhydrous ones, as well as being related to salt agglomeration in thin layers of the material due to repetition of wet/dry cycles [22]. Additionally, concrete dried at temperatures higher than 50°C can show cracking that could alter absorption [3] and [13]. However, the strength of concrete cannot be evaluated solely on water absorption [8].

The deteriorating effect of cyclic wetting and drying in MgSO$_4$ solution on the $f'c$ cubes was observed to be greater than that of cyclic wetting and drying in water, potentially due to the multiple hydrated forms of these magnesium sulphate solutions as MgSO$_4$, forms gypsum and ettringite. The reaction between Mg$^{2+}$ and Ca(OH)$_2$ also causes brucite (Mg(OH)$_2$) to be produced, while the decalcification of CSH introduces magnesium silicate hydrate (MSH), which has no binding effect [15]. Finally, MgSO$_4$ can cause crack growth across the bulk of the stone in a very aggressive manner [22]. The $f'c$ for M-SSP5 was highest, followed by that for M-SSP10, potentially because of the contribution of SSP to the
strength of the concrete. The increased pozzolanic effect enhances the chemical composition and physical characteristics of the concrete in terms of particle packing [23]. It has also been noted, however, that where the effectiveness of the cement is higher, the pozzolanic reaction is reduced for pozzolans with constant efficiency [24], [25].

![Figure 9](image_url)

**Figure 9.** Strength results for different RCC mixes after wetting and drying cycles: (a) \( f'c \) and (b) \( f_r \).

The results reveal that M-R satisfies the target \( f'c \) requirements despite cyclic wetting and drying exposure, due to the presence of SSF acting as a reinforcing material [26], [15]. The \( f'c \) results for M-SSP20 were underestimated, however, perhaps due to the higher pozzolan percentage leading to the cement content being reduced below the optimum, reducing the amount of lime available, and decreasing pozzolanic efficiency [24]. Under drying conditions, salt solutions could also rise to the surface of the concrete by means of capillary action [3] and [13], and the degree of crystallisation pressure and pore filling, plus the micro-mechanical properties of the material may lead to the instigation of cracks or even complete disintegration [22], [27]. The trends observed for \( f'c \) were also noticed for the \( f_r \) of RCC prisms, as shown in Figure 9 b. The interpretations as given for the \( f'c \) results may thus be applied for the \( f_r \) results. Excessive loss in flexural strength could also be explained by the formation of cracks that are highly sensitive to bending (flexural) load [9], [7].

Figures 10 a and b reveal that the UPV results for RCC cubes and prisms, respectively, are in line with the mechanical strength results, with the UPV decreased for different exposure cycles with an increase in the level of damage or decreasing as the time of exposure is prolonged, particularly with regard to drying time [28], [10], and [29]. This may be because of micro-cracks created as a result of the drying process that increase travel time and decrease pulse velocity, as sound is transported in empty pores with lower UPV [30], [21]. It was also noted that the UPV results for M-SSP5 and M-SSP10 were higher compared to those of the control mix for the same cycle, supporting the micro-filling and pozzolanic effect of SSP on the properties of RCC mixes [31], [32], [6]. MgSO_4 exposure again had a greater deteriorating effect on concrete specimens than water exposure [15], [22], with the UPV results for M-SSP5 being highest, followed by those for M-SSP10. This could be due to the effects of crystalline silica in concrete [32]. The lowest UPV value was for M-SSP20, most likely for similar reasons as offered for the \( f'c \) results [24]. There was no clear variation between the UPVs of cubes and prisms.

The results of absorption testing are shown in Figure 11. The absorption% for all RCC mixes increased with the increasing number of cycles, and cyclic wetting and drying in MgSO_4 solution led to increases in absorption increase rates as compared to water exposure. However, the
absorption results for the same cycle decreased for M-SSP5 and M-SSP10 as compared to the control mix due to the micro-filling and pozzolanic effects of SSP on the properties of RCC mixes [31], [32], [6]. The absorption% of M-SSP5 was recorded as being the lowest, followed by M-SSP10, then the M-R mix, while M-SSP20 achieved the highest absorption%. The reasons are again similar to those offered for differences in $f'c$ and UPV [23], [24].

![Figure 10. UPV of (a) cubes and (b) prisms after wetting and drying cycles for different RCC mixes.](image)

The behaviour of the volume of permeable voids% was the same as that of the absorption%. The results are shown in Figure 12. The volume of permeable voids% increased as the cyclic wetting and drying increased, with MgSO$_4$ causing more degradation than water. In cyclic water exposure, accumulative micro-cracking caused by the wetting-drying cycles occurs [12], [10], so that alongside higher “surface” water absorption, increases in permeability and decreased resistance to sulphate attacks are seen in such concrete [8]. For M-SSP5 and M-SSP10, employing pozzolans at the optimum replacement ratio in CMs could decrease the permeability coefficient [26]. The highest permeability was observed for M-SSP20, for reasons as mentioned for $f'c$ and absorption [24].
The density (∆) results are presented in Figure 13. The density decreased as the cycles increased for both exposure types, with greater effects seen from the MgSO₄ solution [15], [22]. The results for density reflect the absorption and volume of voids behaviours observed above, and are in line with the mechanical properties results, as mentioned in [33], [34]. The same reasons used to explain the strength and volume of permeable voids behaviours can thus also be used to explain the density results. M-SSP5 and M-SSP10 achieved the highest densities [23], [24], while M-SSP20 showed the lowest density [24]. The test results for (non-exposed) RCC mixes after 28 days (normal curing) are presented in Table 5.

**Figure 11.** Absorption after wetting and drying cycles for different RCC mixes.

**Figure 12.** Volume of permeable voids after wetting and drying cycles for different RCC mixes.

**Figure 13.** Density of hardened concrete (∆) of cubes after wetting and drying cycles for different RCC mixes.
Table 5. Tests results for non-exposed specimens of different RCC mixes

| Mix ID   | $f'c$ (MPa) | $fr$ (MPa) | UPV (mm/µs) for Absorption% | The volume of permeable voids% | Density, $\rho$ (gm/cm$^3$) |
|----------|-------------|------------|-----------------------------|------------------------------|-----------------------------|
|          |             |            | Cubes | Prisms |                           |                             |                             |
| M-R      | 47.3        | 9.85       | 4.890 | 4.898  | 1.542                      | 4.355                       | 2.400                       |
| M-SSP5   | 48.4        | 10.71      | 5.002 | 4.929  | 1.417                      | 4.014                       | 2.425                       |
| M-SSP10  | 42.9        | 8.06       | 4.779 | 4.745  | 1.518                      | 4.422                       | 2.374                       |
| M-SSP20  | 28.5        | 4.69       | 4.524 | 4.573  | 1.509                      | 4.554                       | 2.256                       |

5. Conclusions
Within the limitations of this study, the following deductions may be made:
1. Using SSP as partial substitution for cement up to 10% by weight of cement is feasible.
2. The optimum SSP substitution percentage is likely to be 5% by weight of cement based on durability considerations.
3. The damaging effect of cyclic wetting and drying in $\text{MgSO}_4$ solution is greater than that of cyclic wetting and drying in water.
4. The degradation of concrete increases as the number of wet/dry cycles increases (deterioration increases with time): the decreases in $f'c$ and $fr$ for the M-R mix after 30 and 60 cycles of $\text{MgSO}_4$ exposure were 1.95% and 1.67%, respectively with similar trends observed for other mixes.

References
[1] Şahmaran M and Li V C 2016 Suppressing alkali-silica expansion using ECC for extended infrastructure service life Mag. ci Conc. Int. 38 76
[2] Drimalas T, Clement J C, Folliard K J, Dhole R and Thomas M D 2011 Laboratory and Field Evaluations of External Sulfate Attack in Concrete Texas Department of Transportation Center for Transportation Research Austin USA Technical Report No. FHWA/TX-11/0-4889-1 p 190
[3] Van Dam T J 2016 Ensuring Durability of Concrete Paving Mixtures-Part I: Mechanisms and Mitigation Federal Highway Administration USA tech brief FHWA-HIF-16-033 p 12
[4] ACI 201.2R 2016 Guide to Durable Concrete American Concrete Institute Farmington Hills MI USA p 84
[5] Sarkar K and Bhattacharjee B 2014 Wetting and drying of concrete: Modelling and finite element formulation for stable convergence j. Struct. Eng. Int. 24 192–200
[6] Ramezanianpour A A, Mirvalad S S, Aramun E and Peidayesh M 2010 Effect of four Iranian natural pozzolans on concrete durability against chloride penetration and sulfate attack Proc. 2nd Int. Conf. on sustainable construction materials and technology ed. Claisse P, Ganjian E, Canpolat F and Naik T (Ancona: Italy)
[7] Sarsam S, AL-Rawi A and Tawfeeq S 2013 Assessing Durability of Roller Compacted Concrete Sustainable Pavement Proc. 9th Int. Conf. on Concrete for Sustainable Construction (Kingdom of Bahrain) p 14
[8] Zhang S P and Zong L 2014 Evaluation of relationship between water absorption and durability of concrete materials j. Advvs. in Mats Sci. and Eng. 2014 8
[9] Arel H Ş and Thomas B S 2017 The effects of nano-and micro-particle additives on the durability and mechanical properties of mortars exposed to internal and external sulfate attacks j. Res. in phys. 7 843–51
[10] Yu X T, Chen D, Feng J R and Zhang Y 2018 Behavior of mortar exposed to different exposure conditions of sulfate attack j. Ocean Eng. 157 1–12
[11] Kencanawati N N, Anshari B, Paedullah A G and Shigeishi M 2018 The study of ultrasonic pulse velocity on plain and reinforced damaged concrete MATEC Web of Conf. 2018 EDP Sciences vol 195 p 02026

[12] Achour R, Zentar R, Abriak N E, Rivard P and Gregoire P 2019 Durability study of concrete incorporating dredged sediments Case Studies in Construction Materials 11(2019) e00244

[13] Ting M Z Y, Wong K S, Rahman M E and Meheron S J, 2020 Deterioration of marine concrete exposed to wetting-drying action Journal of Cleaner Production 278 p 123383

[14] Zhutovsky S and Hooton R D 2016 Evaluation of Concrete’s Resistance to Physical Sulfate Salt Attack. Service Life of Cement-Based Materials and Structures Proc. of the Int. RILEM Conf on Materials, Systems and Structures in Civil Engineering Conference segment on Service Life of Cement-Based Materials and Structures Technical University of Denmark (Lyngby: Denmark)

[15] De Souza D J, Medeiros M and Hoppe F J 2020 Evaluation of external sulfate attack (Na2SO4 and MgSO4): Portland cement mortars containing fillers j. Struct. and Mats. IBRACON 13 644–55

[16] Shafigh P, Hashemi M, Nam B H and Asadi I 2020 Laboratory comparison of roller-compacted concrete and ordinary vibrated concrete for pavement structures Gradevinar 72 127–37

[17] ACI 327. R 2015 Guide to Roller-Compacted Concrete Pavements American Concrete Institute Farmington Hills MI USA p 56

[18] ACI 211.3R 2000 (09) Guide for Selecting Proportions for No-Slump Concrete American Concrete Institute Farmington Hills MI USA p 26

[19] Abed Z M and Salih A A 2017 Effect of Using Lightweight Aggregate on Properties of Roller-Compacted Concrete ACI Materials Journal 114 pp 517-25

[20] Rahim A S, Al-Rawi A A and Sarsam S I 2012 Laboratory investigation on roller compaction technique in concrete construction J. of Eng. 18 423-32

[21] Godinho J, Junior T D, Medeiros M and Silva M 2020 Factors influencing ultrasonic pulse velocity in concrete j. Struct. and Mats. IBRACON 13 222–47

[22] Lubelli B et al. 2018 Towards a more effective and reliable salt crystallization test for porous building materials: state of the art j. Mats. and Structs. 51:55 21

[23] ACI 232.1R 2012 Report on the Use of Raw or Processed Natural Pozzolans in Concrete American Concrete Institute Farmington Hills MI USA p 29

[24] Dunstan ER 2011 How Does Pozzolanic Reaction Make Concrete Green World of Coal Ash (WOCA) Conf. Ash Library Denver CO USA p 114

[25] Mehmannavaz T, Sumadi SR, Bhutta MA, Khorraram VK and Sajjadi SM 2012 Permeability of The Roller Compacted Concrete: A Case Study of Zirdan Dam of Iran APSEC-ICCIER, ed. Norhazilin Md Noor et al. (Surabaya: Indonesia) pp 474-81

[26] Platias S, Vatalis K I and Charalampides G 2014 Suitability of quartz sands for different industrial applications Int. Conf. on App. Econs. (ICOAE) Proc. Econs. and Finance vol 14 pp 491-98

[27] Ragoug R Omikrine-M O Torrenni J-M Barberon F Divet L and Roussel N 2016 Proc. of The Workshop External Sulfate Attack–Influence of an early age exposure, coupling with the cement composition (Portugal: Lisbon) pp 57–68

[28] Chen H, Qian C, Liang C and Kang W 2018 An approach for predicting the compressive strength of cement-based materials exposed to sulfate attack PLoS ONE 13 p e0191370

[29] Guo J-J, Wang K, Guo T, Yang Z-Y and Zhang P 2019 Effect of Dry–Wet Ratio on Properties of Concrete Under Sulfate Attack Materials 12 p 16
[30] Sarsam SI, Al-Rawi A and Tawfeek SD 2014 Assessing the impact of cement content and type on the durability of roller compacted concrete using NDT *IJSRK* **2** 48

[31] Durga B and Indira M 2016 Experimental Study on Various Effects of Partial Replacement of Fine Aggregate with Silica Sand in Cement Concrete and Cement Mortar;"* International Journal of Engineering Trends and Technology (IJETT)* **33** pp 252-56

[32] Korkmaz KA and Ashur S 2019 Experimental investigation of crystalline silica in concrete *Athens J. of Tech. & Eng. (AJTE)* **6** 101–14

[33] Fardin HE and Santos AG 2020 Roller Compacted Concrete with Recycled Concrete Aggregate for Paving Bases *J. Sustainability* **12** 3154

[34] Zhao G Shi M Guo M and Fan H 2020 Degradation Mechanism of Concrete Subjected to External Sulfate Attack: Comparison of Different Curing Conditions *J. Materials* **2020** **13**