Some Properties of RCC Containing Silica Sand Powder Exposed to MgSO₄ Solution

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Abstract. Roller compacted concrete (RCC) is a special type of concrete with zero or even negative slump consistency. This work has been targeted to produce and investigate the durability of an RCC mix suitable for roads paving with better engineering properties. Different RCC mixes have been prepared using micro natural silica sand powder (SSP) as a partial substitution by weight of sulfate resistant Portland cement, i.e., [0% (M-R), 5% (M-SSP5), 10% (M-SSP10), and 20% (M-SSP20)]. Additionally, M-sand, crushed stone (NMSA of 19.0 mm), filler, and water were used. Materials have been proportioned according to ASTM D1557. Slabs prepared and cast in molds with dimensions of 38×38×10cm using a vibrating table and manually operated human-made rolling device. Sawing was made after 28 days of normal curing to obtain cubes of 10×10×10cm and prisms of 10×10×38cm used for different tests. Continuous full immersion in 5% MgSO₄ solution at a temperature of (23±2)°C for 60 and 120 days was implemented to investigate the durability of RCC specimens. The compressive strength (f'cu) of M-SSP5 increased by 7.35% and 7.14%, and the flexural strength (fr) increased by 32.1% and 33.67%, after 60 and 120 days of exposure, respectively, compared to the control mix.

Keywords. RCC, Silica powder, MgSO₄ Solution.

1. Introduction
Nowadays, it is recommended to deal with concrete paving mixes that are workable, reliable, and durable, in which the cementitious materials (CMs) are approximately 324 kg/m³ or less [1]. In this context, roller compacted concrete (RCC) is a specific type of concrete like conventional concrete from the view of the materials (coarse, fine aggregates, cement, and water). However, unlike traditional concrete, the RCC mix is drier and has the feel and consistency of moist gravel [2]. RCC could be considered as a competitive alternative for streets and highways, highway shoulders, parking. Moreover, airport aprons; highway weigh stations. RCC could also be applied as a base material in composite systems [3], [4]. Figure 1 shows the multiple characteristics of RCC pavements.
Silica sand, or quartz-rich sand, is a mineral resource combined with oxygen and silicon [6] and [7]. It is a primary compound of sand, rock, and mineral ores with a high silica proportion that could be up to 99% SiO$_2$ in a crystalline form. The high specific surface area and the specified particle size range make it suitable for use in many applications other than as aggregate [8] and [9]. In Iraq, silica sand deposits are available in the western region at Al-Anbar Governorate with abundant quantities, low prices, and useful characteristics [10], [11]. Silica sand has a diversity of applications such as construction, foundry, glass industry, which are the most common thereof [12] & [13]. The deterioration of concrete structures is accelerated when aggressive chemicals such as sulfate salts found in soil or dissolved in groundwater penetrate the concrete, causing an expansive reaction that attacks the cementing materials through ettringite formation, which may cause extensive damage. This process may result in a gradual loss of concrete strength accompanied by surface spalling and exfoliation [14], [15], and [16], [17] stated that well-processed manufactured sand could result in better particle packing. This packing leads to an increase in the binding effect with cement paste and improves the f’c [18] Its most refined forms, such as flour, micro-silica, quartz sand, could be used as a reinforcement filler. [19] mentioned that silica sand is a pozzolanic material, which could produce compounds of cementing abilities and could be employed as aggregates for lightweight concrete. The f’c of mortars could be improved, which means the crystalline phase in quartz sand will not be an obstacle to its pozzolanic activity. The replacement of cement by ground (pulverized) quartz sand will increase the water requirements [20], [21].

Prisms exposed to MgSO$_4$ had the most significant value of expanding all the sulfate types and showed large cracks rather than deteriorating noticed in Na$_2$SO$_4$ prisms. It also had mentioned that the magnesium sulfates (MgSO$_4$) could react with all hydrated cement compounds and had generally considered being the most damaging form of sulfates. Equation (1) shows the reaction process.

$$3\text{CaO}.2\text{SiO}_2 + \text{Mg}^2\text{SH}_2 \rightarrow 3(\text{C}^-\text{SH}_2^-) + 3\text{Mg}^2\text{O} + 2\text{S}$$

It had been mentioned by [23] that the cracking and failure of the concrete is a function of sulfate attack, weathering, and higher permeability) through micro cracking and not only due to sulfate attack, where a de-cohesion and loss of structure’s strength would result from the decomposition of cement hydrates.

The ultrasonic pulse velocity had studied by Merida & Kharchi [16]. It had been noticed that for both non-pozzolan and pozzolan concrete specimens (cured in water for one year), the UPV had increased by 1.43% & 2.68%, respectively. However, the UPV of specimens for both concretes exposed to 5% Na$_2$SO$_4$ solutions for one year had decreased by 3.4% and 1.58 %, respectively.

Two sodium sulfate solutions with concentrations of 10% and 20% had been used. Concrete specimens were immersed and found that the damage degree of the concrete increased with the immersion time. The f’c results had presented in Figure 2 [24]. Arel and Thomas, [25], studied the strengths, expansion, and durability of mortar mixtures exposed to external and internal sulfate attack. Normal curing was applied to all mortar samples for 23 weeks. The results are presented in Table 1.
Table 1. Compressive and flexural strengths of reference specimens by [25].

| Specimen               | Average Strength (MPa) |
|------------------------|------------------------|
|                        | Compressive | Flexural     |
| Reference in Water     | 59.1         | 6.4          |
| Reference in Na$_2$SO$_4$ | 33.6         | 2.7          |
| Reference in MgSO$_4$  | 30.2         | 2.1          |

[26] mentioned that after the standard curing of 28 days, the cylindrical mortar samples of (Φ50×100) mm and prismatic bars of (25×25×285) mm had subjected to full-immersion; 5% Na$_2$SO$_4$ solution; 20±2°C up to 270 days (sulfate solution were refreshed every two months) had led to chemical sulfate in the mortar. The expansive products (gypsum and ettringite) first filled the internal pores, later exceeded accommodation capacity, and induced micro-cracking.

Mixes, i.e., C1 and C2, had continuously soaked in a 5% Na$_2$SO$_4$.10H$_2$O solution at 23°C for five months of total immersion. Figure 3 shows the differential porosity obtained over one and two (T1&T2) months of exposure. It has been noticed that the porosity increased by 5.9% for C1 and by 3.0% for C2 during the total immersion process [27], [28] had studied and compared different RCCP and standard strength concrete (NC) mixes. The results at 28 days revealed that the flexural strength ($f_r$) of RCCP mixes increased by approximately 19.6 % and 30.1 % due to the densely packed aggregates where the $f_r$ is directly related to the density and $f'$c of concrete. The $f'$c results showed an 8 % to 10 % increase. For all RCCP mixes, the water absorption had decreased by 3%. [29] indicated that replacing the cement with the quartz filler showed better behavior towards the sulfate. The researchers also revealed that the magnesium sulfate solutions would form magnesium silicate hydrate (MSH), which has no cementing properties. In addition to the formation of other harmful products. According to [30], it had been mentioned that the porosity would affect the RCC adversely, while the dry density has to show a positive effect on compressive strength when it had increased. The importance of RCC compaction for obtaining better mechanical properties also had proved.

2. The aim of the study
This study aims to produce RCC mixes and investigate their durability against external sulfates attacks to achieve better engineering properties. A partial replacement of cement weight by (5, 10, and 20) % of natural (micro) silica sand powder (SSP) has suggested since it has available abundantly in Iraq at a very low cost.
3. Experimental work

3.1. Materials
Crushed Stone (CS) was brought from Al-Nibaee region to the north-west of Baghdad/ Iraq and used as coarse aggregate in this work with an NMAS of 19 mm and sulfur content (SO$_3$) of 0.056%. The specific gravity and absorption were (2.632, 0.49%), respectively. Manufactured sand (M-Sand) was used as fine aggregate in this work, and it was brought from the same source of CS with a sulfur content (SO$_3$= 0.309%). The specific gravity and absorption were (2.591, 2.34%), respectively. The M-sand and CS aggregates have satisfied the limits of the Iraqi specification IQS No. 45 and ASTM C33/33M. The combined grading used in this work was selected to meet the gradation of type II (binder course) by State Commission for Roads and Bridges SCRB/R9, as shown in Figure 4. Silica Sand Filler (SSF), natural silica sand, i.e., a white (non-plastic) material, was brought from Iraq/ the Western area/ Al-Anbar Governorate/ Urduma region and used as a filler (100 % passing sieve 0.075 mm). The specific gravity and absorption were (2.6, 0.4%), respectively. Type V Portland cement/ Al-JESR was used for the RCC mixes. The cement properties are shown in Table 2; they are conformed the Iraqi specification No. 5 and ASTM C150. Silica sand powder (SSP) (specific gravity =2.61) used in work was obtained by mechanical grinding for the natural silica sand using an electrical mill brought from the same source as SSF. The properties of SSP had compared with ASTM C 618 and presented in Table 3. Tap water had used for mixing and curing concrete batches. The (required/ target) compressive strength ($f'_{cu}$) for all RCC mixes had followed the SCRB/R10, which specified a minimum $f'_{cu}$ of 30 MPa for roads paving. All materials have been tested in the National Center for Construction laboratories and research (NCCLCR).

![Figure 4. Gradation of combined aggregate.](image)

| Chemical Properties | Physical Properties |
|---------------------|---------------------|
| SiO$_2$ % +         | Strength Activity Index at 28days |
| Fe$_2$O$_3$ %       | Loss on Ignition (LOI), % |
| Al$_2$O$_3$ %       | Moisture Content % |
| results             | Retained % on Sieve No. 325 |
| ASTM C 618 (Class N), Requirements | 70 Min. 4 Max. 10 Max. 3 Max. 34 Max. 75 Min. |
| SO$_3$ % + SO$_4$ | 92 |
| content             | 1.65 |
| 8                   | 1.6 |
| 34 Max.             | 20 |
3.2. Proportioning, mixing, mold description

The ASTM D1557-method C was used for proportioning RCC mixes, as suggested by ACI 327.1R [2] and ACI 211.3R [3]. Different moisture contents have been added, i.e., (0.045, 0.05, 0.055, 0.065, 0.075, and 0.085), to identify the suitable/optimum water content (OMC %) against maximum dry density, \( \gamma_{\text{dry max}} \) (gm/cm\(^3\)) for each mix. The results of ASTM D1557 are illustrated in Table 4. For proportioning RCC mixes, M-Sand and CS were used in percentages of 47% and 49%, respectively. Also, 4% of fines (SSF) were used; all aggregates were selected according to gradation results. Cementitious materials are composed of type V Portland cement, which was replaced by different percentages, e.g., (5 %, 10 %, and 20 %) of SSP on a weight basis, the mixes had designated by (M-SSP5, M-SSP10, M-SSP20) in addition to the control mix, M-R (0 %) of SSP.

| Mix-ID | Mix-Description | OMC % | Dry Max. (gm/cm\(^3\)) |
|--------|-----------------|-------|-------------------------|
| M-R    | RCC-0%SSP 100% Cement | 5.800 | 2.342                   |
| M-SSP5 | RCC-5% SSP 95% Cement | 6.040 | 2.356                   |
| M-SSP10| RCC10% SSP 90% Cement | 6.170 | 2.367                   |
| M-SSP20| RCC20% SSP 80% Cement | 6.366 | 2.312                   |

The quantities of materials for each RCC mix have been calculated, as illustrated in Table 5. Figure 5 shows an RCC dry mix, and Figure 6 shows a mix in a proctor mold.

| Mix-ID | Mix-Description | Materials Weights, kg | W/CMs |
|--------|-----------------|-----------------------|-------|
|        |                 | Cement | SSP | M-sabd | 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 |

The used mold to cast RCC slabs with handles for handling is shown in Figure 7. Before placing the RCC mix in the mold, it was wiped where the mix is placed; nylon sheets are used to prevent emitting the moisture and fine materials of the mix from the mold sides. The mixing method had followed the ASTM C192/C192 M.
3.3. Compaction

3.3.1. Vibrating table compaction. Firstly, each RCC mix is subjected to densification using a vibrating table, as shown in Figure 8. Each mix was placed in the mold as three layers, and each layer was vibrated for 30s ASTM C1170. The vibration could produce some initial compaction as in the field ACI 327. R [2]. After the vibration process was completed, the finished surface should not tolerate more than 3 mm above the mold thickness ASTM C1170.

3.3.2. Manual compaction (by a hand-made roller device). For final compaction, a roller device made in a local workshop was used, as shown in Figure 9. A procedure adopted by a group of researchers [32], [33] was implemented. The compaction was done on plain ground, as shown in Figure 10. Two directions densification, (x-x) and (y-y), were executed to ensure uniformity. A procedure of three parts-compaction was as follows:

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

Part 2. Compaction using additional weights to the device weight (38) kg +74 kg =112 kg, which was put in the steel box of a roller device; a static linear load of 3.2 kg/cm; and (10-12) passes.

Part 3. Compaction using the weights (38) kg +74 kg + 74 kg =186 kg (additional weights were used as burdens); a static linear load of 5.3 kg/cm; and (10) passes.

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**Figure 7.** RCC mold.  
**Figure 8.** RCC mold on a vibrating table.  
**Figure 9.** RCC roller device.  
**Figure 10.** Compacted mix.
3.4. Curing
Initial and final curing was done as recommended by ASTM C192/C192 M after the rolling was finished. The molds have been protected against moisture loss using a layer of burlap (jute) cloths and nylon sheets and left at room temperature for 24 hrs for initial curing. Figure 11 shows a sample of RCC slab prepared at the initial curing. The final curing was done by immersing the RCC slabs samples in a water receptacle at a temperature of (22)° C for 28 days, as shown in Figure 12.

![Figure 11. Initial curing of RCC sample.](image1)

![Figure 12. Final curing of RCC slabs.](image2)

3.5. Sawing RCC slabs
To obtain RCC cubes and prisms, a saw cut was used to make them according to ASTM C42/C42M. Cured slabs of (38×38×10) cm in dimensions were sawn to get cubes of (10×10×10) cm and prisms of (38×10×10) cm. A steel-diamond saw disk was used in two stages:

1. Cutting after 7-day of curing, for each RCC mix, i.e. (M-R, M-SSP5, M-SSP10, and M-SSP20) a No. of slabs were sawed to find if it was possible to have perfect specimens at 7-day age. Unfortunately, the sawing at that age has affected the samples negatively. The immaturity of RCC slab samples could lead to concrete disintegration, as shown in Figure 13. Subsequently, the results at the age of 7 days could not be considered.

2. Cutting after 28 days of curing. When the concrete had reached the expected hardening, it could be assumed to sustain cutting, as shown in Figure 14. Each slab was sawn into three cubes and two prisms.

![Figure 13. RCC sawed prism after the age of 7 days.](image3)

![Figure 14. Sawed samples at the age of 28 days.](image4)
3.6. Exposure system

After the specimens were cured in water for 28 days, the external sulfate attack investigation was applied based on ASTM C88 and ASTM C1012 specifications and work adopted by several researchers, e.g. [34], [22], and [27]. The sawed specimens were fully immersed in a 5% of MgSO₄ solution at a temperature of (23±2°C) for 60 and 120 days (the solution refreshed every four weeks). The sawed specimens were placed in a suitable plastic container at the conditions and durations mentioned above. The solution was ensured fully covering the specimens from all sides and surfaces, as shown in Figure 15a.

3. The plastic container was closed tightly by its lid, as shown in Figure 15b, to prevent the evaporation of the solution and avoid any contamination or dilution with water from outside sources. After specimens being left in the MgSO₄ solution for 60 and 120 days, respectively, they would be prepared for destructive and non-destructive tests.

![Figure 15](image1.png)

Figure 15. Arrangement of some RCC sawed specimens submerged in a container filled contains MgSO₄ solution (a) Opened container (b) Closed container

4. Testing

4.1. Compression test

The BS EN, 12390-3, were used to test $f'cu$ of cubes (10×10×10) cm after each exposure, as shown in Figure 16.

4.2. Flexural strength test

ASTM C78 (third point loading + simple beam) was used to find $fr$ of prisms (38×10×10) cm after each exposure, as presented in Figure 17.

![Figure 16](image2.png)

Crushing machine loading rate: 0.3 N/mm²/sec
Capacity: 3000 KN

Flexural machine loading rate: 0.04 N/mm²/sec
Capacity: 100 KN

![Figure 17](image3.png)

Figure 16. RCC cube during compression.  
Figure 17. RCC cube during flexural.
4.3. Absorption%, Voids %, and Density Test
ASTM C 642 was used to specify the percentage of absorption, permeable voids, and density for different RCC mixes using cubes of (10×10×10) cm after each exposure, as shown in Figure 18.

4.4. Pulse Velocity (UPV) test
The MATEST device was utilized for checking the UPV. The test has done based on ASTM C597 for all specimens after each exposure, as shown in Figure 19.

5. Results and discussion
The results of $f'$cu for different RCC mixes after 60 and 120 days of exposure are presented in Figure 20. and Table 6. It can be noticed that as the time of exposure is increased, the $f'$cu decreased for all RCC mixes [35], [36]. Additionally, even the RCC mixes that have been subjected to severe exposure conditions, the M-R, M-SSP5, and M-SSP10 mixes still satisfy the targeted strength of 30 MPa. It can be observed that the M-SSP10 has overpassed the M-R mix when exposed to MgSO$_4$, which proves the positive effects of incorporating SSP in RCC [37], [16], [14]. However, the M-SSP5 mix has achieved the highest $f'$cu results, followed by M-SSP10. The increase in strength of M-SSP5 and M-SSP10 mixes, respectively, compared to the M-R mix, could be due to the pozzolanic reaction that occurs in the existence of moisture when reactive SSP elements in the CMs reacts with (CH) [a product of the Portland cement hydration]. So, additional C-S-H would be formed, which typically improves concrete [2], [1]. These results are in line with [38] and [39]. Also, the increased strength may be due to the reduced rate of the heat of hydration (as a result of employing SSP), which leads to minimizing the potential of initial cracking and external attacks in concrete specimens [20], [21]. Also, it has been mentioned that the pozzolans contribute to the strength of concrete due to the physical characteristics in terms of particle packing in addition to their chemical composition [40].

Figure 21 and Table 6 show the results of $fr$ after 60 and 120 days of exposure. The performance of $fr$ was comparable to that of $f'$cu, for different RCC mixes, where the M-SSP5 has achieved the highest $fr$ followed by M-SSP10 the same reasons that have interpreted the $f'$cu results would explain the behavior of $fr$ test. However, the increase/decrease in $fr$ was more than that was noticed in $f'$cu results. This difference could be due to the fact that $fr$ tends are affected by the content of fines and the age of the tested specimen more than $f'$cu [41].
For M-SSP20, it has exhibited a decrease in mechanical strengths after exposure to MgSO₄. This decrease could be because of a higher pozzolan percentage than optimum cement content anticipated, so a lower amount of lime was available. As a result, the pozzolanic efficiency would be reduced. The \( f'_c \) of RCC mixes was directly related to the density and \( f'cu \) [42], [2]. So, it can be noticed that the results of density are in line with the \( f'_c \) results.

\[ \text{Table 6. The results of } f'_c, f'_r, \text{ and } UPV \text{ for cubes and prisms after 60 and 120 days of CFI in MgSO}_4 \text{ solution for different RCC mixes} \]

| Mix ID  | 60 days | 120 days |
|---------|---------|----------|
|         | \( f'_cu \) (MPa) | \( f'_r \) (MPa) | UPV for Cubes | UPV for Prisms | \( f'_cu \) (MPa) | \( f'_r \) (MPa) | UPV for Cubes | UPV for Prisms |
| M-R     | 42.2    | 7.20     | 4.669     | 4.675       | 42.0          | 6.98        | 4.502       | 4.508       |
| M-SSP5  | 45.3    | 9.51     | 4.814     | 4.817       | 45.0          | 9.33        | 4.771       | 4.778       |
| M-SSP10 | 42.7    | 7.75     | 4.715     | 4.718       | 42.5          | 7.71        | 4.699       | 4.700       |
| M-SSP20 | 28.4    | 4.28     | 4.115     | 4.117       | 27.7          | 4.19        | 4.102       | 4.104       |

Figures 22a and 22b, in addition to Table 7, show the results of density, absorption, and volume of permeable voids for different RCC mixes. It can be noticed that as the replacement percentage of SSP has increased up to 10%, the \( \rho \) density also increased, while the absorption and volume of voids have decreased. This increase could be due to the addition of SSP, which would increase the packing density in addition to the pozzolanic efficiency [40], [19] [39]. Additionally, maybe due to the reduced rate of the heat of hydration (as a result of employing SSP), which leads to minimizing the potential of initial cracking and external attacks in concrete specimens [20], [21]. Also, in RCC mixes the lower w/cms and good compaction, water absorption reduction could happen [28], [43]. The absorption results are in line with [44]. Since the porosity could affect the RCC adversely [27], employing pozzolan using the optimum replacement ratio in CMs would decrease the porosity [45], [30]. M-SSP20 has a lower density and the highest absorption and volume of permeable voids. The reason could be that the increase in replacement percentages had increased porosity and absorption due to an increase in paste volume, leading to an increase in voids volume [46]. However, those results of M-SSP20 were comparable to those mentioned for the mechanical strength results.
Figure 22. Absorption, the volume of permeable voids, and density of different RCC mix after (a) 60 days of exposure, (b) 120 days of exposure.

Table 7. Density (ρ), absorption, the volume of permeable voids results, after 60 & 120 days of CFI in MgSO₄ solution for different RCC mixes.

| Mix ID  | 60 days Density (ρ) | Absorption % | The volume of permeable voids % | 120 days Density (ρ) | Absorption % | The volume of permeable voids % |
|---------|---------------------|--------------|---------------------------------|----------------------|--------------|---------------------------------|
| M-R     | 2.389               | 2.943        | 6.537                           | 2.382                | 3.442        | 7.035                           |
| M-SSP5  | 2.421               | 1.585        | 4.855                           | 2.419                | 1.64         | 4.915                           |
| M-SSP10 | 2.371               | 1.646        | 4.926                           | 2.368                | 1.689        | 5.015                           |
| M-SSP20 | 2.185               | 3.934        | 10.201                          | 2.176                | 3.95         | 10.36                           |

For UPV results, as shown in Figures 23a and 23b and Table 6, it could be observed that the results are comparable to mechanical strength results where the UPV decreased as the level of damage increased, which means that the higher the damage level, the lower the velocity observed [47]. The M-SSP5 showed the highest value of UPV, followed by M-SSP10, and a lower UPV has been noticed in M-SSP20. The reasons could be due to as that mentioned for density results. The corresponding results UPV have mentioned by [48].

Figure 23. UPV for different RCC mixes after 60 and 120 days of exposure (a) for cubes and (b) for prisms.
6. Conclusions
Based on the results of this study, the following conclusions could be listed:

1. The SSP could be used up to 5% for durability considerations and up to 10% for economic reasons according to the project’s priorities.
2. The M-SSP5 has achieved the highest mechanical strength results, where the $f'cu$ has increased by 7.35% and 7.14 after 60 and 120 days of exposure, respectively, compared to the control mix. The $fr$ has increased by 32.1% and 33.67% after 60 and 120 days of exposure, respectively, compared to the control mix.
3. The M-SSP5 also achieved the highest density, where it has increased by 1.34% and 1.55% compared to the control mix after 60 and 120 days of exposure, respectively. Additionally, the absorption has decreased by 46.14% and 52.66%; the volume of permeable voids decrement was 25.73% and 30.14% after 60 and 120 days of exposure, respectively, compared to the control mix. The UPV has increased by approximately 3.0% and 6.0% for both cubes and prisms after 60 and 120 days of exposure, respectively, compared to the control mix.
4. The M-SSP10 has achieved satisfactory results. The $f'cu$ has increased by 1.18% and 0.71%, while $fr$ increased by 7.64% and 10.46% after 60 and 120 days of exposure, respectively, compared to the control mix.

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