Early and Long-Term Assessment of High-Performance Concrete Contained Nano-Silica Exposed to Sulfate Attack

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Abstract
This research aims to study the influence of using the Nano-silica in high-performance concrete subjected to external sulfate attack with different levels. Four concrete mixes were prepared by using two types of Portland cement: ordinary and sulfate resistant cement. From each mix, cubic concrete specimens were cast and subjected to different exposure conditions. The concrete cubes were immersed in sodium sulfate (Na2SO4), magnesium sulfate (MgSO4) and calcium sulfate (CaSO4) solutions with concentrations of (1.5, 10 and 15) %. The specimens were tested for compressive strength at (3, 7, 14, 28, 90, 180, 270, 365, and 545) days and the values of sulfate penetration in concrete samples were determined. It can be found from the results that high-performance concrete containing Nano-silica gave a relatively good sulfate resistance compared to the reference sample. Moreover, results indicated that the strength deterioration was reduced after incorporating nano-silica.

1. Introduction
Concrete is one of the most vastly utilized substances in the construction sector [1,2]. However, it may not withstand for long periods due to being attacked by some harmful agents. These aggressive agents can be categorized into two broad denominations, internal and external agents. The external agents include sulfate and chloride ions, carbon dioxide, freeze–thaw cycles and abrasion [3]. The main chemical attack to the concrete in contiguity with an aqueous solution is that correlated with sulfates. The major sulfate chances in ground water are sodium, calcium, magnesium and potassium. Sulfates exist in clays and other soils. The mechanisms of retrogradation rely on the transit of fluids or gasses through the concrete pore structure. The achievement of less permeable concrete is one of the fundamental purposes when trying to get durability. The essential technique for obtaining this is to fabricate a concrete with a low water/cement ratio [4]. High-performance concrete (HPC) is more durable than usual concrete because it is made with a minimizing amount of water so that its microstructure becomes denser with less porosity [5]. However, sulfate, chloride ions, acids or other types of grievous chemicals may attack HPC.

The durability of concrete relies on the microstructural characterization of the hydrated cement paste in the transition zone. In addition, it depends on the evolution of micro cracks that may result from thermal gradients, shrinkage and overloading [6]. During Portland cement hydration, sulfates can able to react with calcium aluminate and free lime causes eventual failure of the concrete. Under sulfate attack, the reaction between the hydrated cement paste and sulfate leads to macro-cracking, spalling and loss of cohesion of concrete [7]. The pores of the concrete microstructure play an important role in...
diffusing the sulfate ions within the concrete. Therefore, the production of concrete with dense microstructure is a worthwhile approach to reduce the effect of harmful ions, including sulfates.

The inclusion of supplementary cementitious materials such as silica fume [8–11], fly ash [12–15], metakaolin [16], ground granulated blast furnace slag [17–20], rice husk ash [21], waste paper [22,23], by-products [24] and steel powder [25] is one of the methods widely used to improve the microstructure of concrete. However, among the recent methods used to improve concrete microstructure is the inclusion of nanoscale materials [26]. Nano-silica is among the most widely used nanomaterials in concrete [27]. The filling effect of the pore structure of concrete provided by nano-silica makes the concrete more homogeneous that leads to enhance strength as well as durability [28]. Many researchers addressed the impact of NS on the sulfate resistance of concrete. Moslemi et al. [29] investigated the effect of replacing cement by 2, 4, 6 and 8% of NS on sulfate resistance up to 180 days. Results indicated that concrete resistance to sulfate attack was increased in the presence of NS. The optimum performance was found at 8% NS replacement level. While Saloma et al. [30] revealed that replacing the cement by 10% NS improved the sulfate resistance of concrete compared to the reference mix (without NS). Vargas et al. studied the influence of replacing cement with 10% NS in lightweight concrete (using two types of lightweight aggregates) under sulfate attack. Results showed that though NS refined the microstructure of concrete, however, the sulfate resistance was mainly affected by the properties of lightweight aggregate used.

According to the above, it can be observed that limited studies are addressed the impact of NS on sulfate resistance of HPC at later ages (more than one year). Therefore, this study is conducted to explore the effect of NS admixture as substitution of cement using two types of cement under three types of sulfate (sodium, calcium and magnesium sulfates) solutions at early and later ages.

2. Experimental work

2.1. Materials

2.1.1. Cement. Two types of cement, ordinary (OPC) and sulfate-resistant cements (SRPC), produced by Tasluja cement factory were used in this study. The physical and chemical properties are shown in Tables 1 and 2 which are conformed to the Iraqi specification (IQS) No.5/1984 [31].

2.1.2. Aggregate. This can be divided into:

(a) Fine aggregate. Local natural sand was used in preparing the concrete mixes. The grading of this sand is compatible with the Iraqi specification No.45/1984 [32] with SO$_3$ content of 0.02 and a specific gravity of 2.64. The grading of sand is shown in Table 3.

(b) Coarse aggregate. Crushed gravel with grading conformed to the Iraqi specification No.45/1984 [32] requirements with SO$_3$ content of 0.013 and specific gravity of 2.66 was used as a coarse aggregate. Table 4 shows the grading of the gravel.

2.1.3 Nano-silica. Nano-silica was incorporated into the mixes as 10% replacement of cement (by weight). Nano-silica with a specific surface area of 150000 m$^2$/kg, average particle size of 14 nm and SiO$_2$ content of > 99% was utilized.
Table 1. Physical properties of OPC and SRPC

| Physical properties                     | Test result | IQS No.5 limits |
|----------------------------------------|-------------|-----------------|
|                                        | OPC         | SRPC            |                |
| Specific surface area (cm²/gm)         | 3575        | 3560            | Min 2300       |
| Initial setting time (minute)          | 94          | 110             | ≥45            |
| Final setting time (hours)             | 4.00        | 5.10            | ≤10            |
| Compressive strength (MPa)             |             |                 |                |
| 3 days                                 | 25.6        | 21.3            | >15            |
| 7 days                                 | 32.5        | 30.2            | >23            |

Table 2. Chemical properties of OPC and SRPC

| Oxide                | Percentage by weight % | IQS No.5 limits |
|----------------------|------------------------|-----------------|
|                      | OPC                    | SRPC            |                |
| SiO₂                 | 21.2                   | 24.7            | ---            |
| CaO                  | 62.0                   | 63.5            | ---            |
| Al₂O₃                | 5.7                    | 3.4             | ---            |
| Fe₂O₃                | 4.2                    | 3.7             | ---            |
| SO₃                  | 2.1                    | 1.4             | ≤2.5 if C₃A ≤ 5% |
| Na₂O+K₂O             | 0.9                    | 0.6             | ---            |
| MgO                  | 2.8                    | 1.56            | ≤5             |
| Loss on Ignition (L.O.I) | 2.27          | 2.16            | ≤4             |
| Insoluble Residue (I.R) | 0.61              | 0.58            | ≤1.5           |
| Lime Saturation Factor (L.S.F) | 0.88          | 0.83            | 0.66-1.2       |
| C₃S                  | 40.92                  | 38.65           |                |
| C₂S                  | 29.9                   | 41.75           |                |
| C₃A                  | 8.01                   | 2.76            |                |
| C₄AF                 | 12.77                  | 11.25           |                |

Table 3. Grading of sand

| Sieve size (mm) | Passing % | IQS No.45 limits (zone 2) |
|-----------------|-----------|---------------------------|
| 10              | 100       | 100                       |
| 4.75            | 98.6      | 90-100                    |
| 2.36            | 85.2      | 75-100                    |
| 1.18            | 63.4      | 55-90                     |
| 0.6             | 46.1      | 35-59                     |
| 0.3             | 23.5      | 8-30                      |
| 0.15            | 1.4       | 0-10                      |
Table 4. Grading of coarse aggregate

| Sieve size (mm) | Passing % | IQS No.45 limits (5-14) mm |
|----------------|-----------|---------------------------|
| 20             | 100       | 100                       |
| 14             | 100       | 90-100                    |
| 10             | 67.3      | 50-85                     |
| 5              | 2.7       | 0-10                      |

2.2. Casting and curing specimens

Four concrete mixes were cast in (100) mm³ cubes. The experimental work included the casting of 912 cubes for compressive strength and sulfate penetration tests. After casting, the specimens were kept in the mold in a suitable place and then were de-molded. Some specimens were immersed in tap water and others with 70% depth of concrete specimens in the salt solution until the test age (3, 7, 14, 28, 90, 180, 270, 360 and 545 days).

2.3. Compressive strength test

The compressive strength test was determined according to BS.1881: part 116 [33] specification. Three cubes were tested for each mix at each age.

2.4. Sulfate resistance test

Concrete sulfate resistance was found by immersing specimens in different concentrations of sulfate solutions. The concentrations of sulfate solutions that were used in previous researches ranged between 1% and 15% [34,35], so the percentages used in this study were chosen to cover the above range. The concrete specimens were immersed in (1.5, 10, 15) % of Sodium, Calcium and Magnesium sulfates solutions (MgSO₄, Na₂SO₄ and CaSO₄, respectively). Then the influence of this immersion on the compressive strength and penetration values in the concrete specimens were observed. Concrete specimens were exposed to two types of sulfate effect:

1. About 70% of the specimens’ depth was continuously immersed in the sulfate solution.
2. About 70% of the specimens’ depth was subjected to wetting-drying cycles weekly.

3. Results and Discussion

First of all, it is worthy to note that the diffused sulfate solutions into the concrete pore react with hydrated cement products. The reaction products of Calcium hydroxide and Calcium aluminate with dissolved sulfate ions have large volumes so that disruption of the paste occurs. This reaction leads to internal pressure in cement paste, the appearance of micro cracks and causing loss of the concrete strength. Generally, it was found from the results (Figures 1 to 8) that the strength of concrete specimens decreased with the increase of sulfate attack. However, in some cases, the concrete specimen's strength increased at the early ages, due to crystallization of reaction yield in the pores of the concrete. The influence of sulfate solutions on the compressive strength of different exposed mixes varied according to sulfate concentration, type of cement and Nano-silica used. It can be seen from figures 1, 2, 3 and 4 that the compressive strength increased for (3, 7 and 14) days when sulfate concentration increased of all mixes and an inverted trend observed for (28, 90, 180, 270, 360 and 540) days. The reaction of external sulfate with Ca(OH)₂ forms gypsum. If all the Ca(OH)₂ are consumed, decalcification of gypsum can occur. Because of the expanded form of the different reaction outputs, the paste structure may be demolished. By comparing these results with work conducted by Oymael [36] who used in his study two types of cement in investigating the impact of Na₂SO₄ and MgSO₄ (in concentrations of 5% and 10%) on concrete properties, it can be observed that the compressive strength was reduced significantly at 14 and 28 days of immersion. While in this study, the compressive strength tended to increase at the corresponding period. This variance in
behavior can be returned to the difference in cement type used in the two studies, which means a
different chemical composition and thus a different reaction mechanism.

For wetting-drying cycles exposure, as presented in figures 5, 6, 7 and 8. Results showed that sulfate
solution increased strength losses. The concrete specimens were immersed in salt solution gave higher
compressive strength than the strength of concrete specimens exposed to the same sulfate solution
with continuous wetting and drying. The use of Nano-silica reduced the strength loss of concrete
specimens due to provide concrete with less porosity.
For the reaction to have happened, the sulfate ions should permeate into the concrete. The values of salt solution penetration into the concrete specimens were measured by cutting the core molds of the concrete specimens to determine the values of salt penetration by changing the color of the concrete to slightly white [37]. It can be seen from figures 9, 10, 11 and 12 that using Nano-silica with concrete mixes has greatly reduced the sulfate solution penetration in the concrete specimens for different exposure conditions.

The values of salt solution penetration in the control samples were greater than those Nano-silica-based mixtures. This due to the filling of concrete pores by the gel formed by the reaction of Nano-silica with calcium hydroxide, or filling these pores with Nano-silica materials, consequently,
increasing concrete density and reducing permeability. However, it is necessary to give sufficient time for Nano-silica before concrete exposed to sulfate solution as shown in figures 9, 10, 11 and 12. Besides, it can be seen from figures 3, 4, 7, 8, 11 and 12 that Nano-silica materials were more effective when used with SRPC.

4. Conclusions and recommendations
The main findings of this study are:
1. HPC durability depends on cement type, sulfates solution percentage and the presence of Nano-silica.
2. The influence of sulfate attack on HPC at early ages (3, 7, 14) days causes an increase in the compressive strength values of all mixes while it cause decreasing in later ages.
3. HPC containing Nano-silica is more durable than that do without Nano-silica because the microstructure of the concrete becomes less porosity, more compact and controlling concrete cracks.

4. There was a significant reduction in the penetration of sulfates into samples containing Nano-silica (30-60%).

5. The concrete specimens that exposed to wet-dry cycles exhibited more deterioration than wet-cured specimens.

Authors recommended using other waste or by-products substances simultaneously with nano-silica, for example, crude oil and agricultural wastes [38–45], industrial wastes [46–48], building materials wastes [49,50], municipal solid wastes [51] as well as water and wastewater planes waste [52–55] to investigate their behavior in concrete or mortar. The application of such materials in the manufacture of reinforced concrete beams [56] is an issue worth examining.

5. References

[1] Hasan Z A, Abed M K and Nasr M S 2019 Studying the Mechanical Properties of Mortar Containing Different Waste Materials as a Partial Replacement for Aggregate Int. Rev. Civ. Eng. 10 155–61

[2] Nasr M S, Shubbar A A, Abed Z A-A R and Ibrahim M S 2020 Properties of eco-friendly cement mortar contained recycled materials from different sources J. Build. Eng. 31 101444

[3] Baker J M, Davies H, Majumdar A J and Nixon P J 2006 Durability of Building Materials and Components: Proceedings of the Fifth International Conference (Routledge)

[4] Balakrishna M N, Rahman M M, Chamberlain D A, Mohammad F and Evans R 2013 Evaluation of test methods for impregnant materials in concrete Int. J. Struct. Eng. Res. 2 213–27

[5] De Larrard F and Sedran T 2002 Mixture-proportioning of high-performance concrete Cem. Concr. Res. 32 1699–704

[6] ACI 201.2 R-08 2008 Guide to Durable Concrete (American Concrete Institute (ACI), Michigan, USA)

[7] Liu K, Deng M, Mo L and Tang J 2015 Deterioration mechanism of Portland cement paste subjected to sodium sulfate attack Adv. Com. Res. 27 477–86

[8] Abed M, Nasr M and Hasan Z 2018 Effect of silica fume/binder ratio on compressive strength development of reactive powder concrete under two curing systems MATEC Web of Conferences vol 162 (EDP Sciences) p 02022

[9] Hasan Z A, Nasr M S and Abed M K 2019 Combined Effect of Silica Fume, and Glass and Ceramic Waste on Properties of High Strength Mortar Reinforced with Hybrid Fibers Int. Rev. Civ. Eng. 10 267–73

[10] Nasr M S, Hussain T H, Kubba H Z and Shubbar A A 2020 Influence of using high volume fraction of silica fume on mechanical and durability properties of cement mortar J. Eng. Sci. Technol. 15 2492–506

[11] Hussain T H, Nasr M S and Salman H J 2019 Effect of elevated temperature on degradation behaviour of reactive powder concrete made with rubber tire wastes as an aggregate replacement ARPN J. Eng. Appl. Sci. 14 775–80

[12] Shubbar A A, Al-Shaer A, AlKizwini R S, Hashim K, Al Hawesah H and Sadique M 2019 Investigating the influence of cement replacement by high volume of GGBS and PFA on the mechanical performance of cement mortar IOP Conference Series: Materials Science and Engineering vol 584 (IOP Publishing) p 12022

[13] Shubbar A A, Al-Jumeily D, Aljaaf A J, Alyafei M, Sadique M and Mustafina J 2019 Investigating the Mechanical and Durability Performance of Cement Mortar Incorporated Modified Fly Ash and Ground Granulated Blast Furnace Slag as Cement Replacement Materials 2019 12th International Conference on Developments in eSystems Engineering
[14] Shubbar A A F, Jafer H M, Dulaimi A F D, Atherton W and Al-Rifaie A 2017 The Development of a Low Carbon Cementitious Material Produced from Cement, Ground Granulated Blast Furnace Slag and High Calcium Fly Ash *Int. J. Civil, Environ. Struct. Constr. Archit. Eng.* 11 905–8

[15] Shubbar A A, Sadique M, Shanbara H K and Hashim K 2020 The Development of a New Low Carbon Binder for Construction as an Alternative to Cement *Advances in Sustainable Construction Materials and Geotechnical Engineering* (Springer) pp 205–13

[16] Nasr M S, Hasan Z A, Abed M K, Dhahir M K, Najim W N, Shubbar A A and Dhahir H Z 2020 Utilization of High Volume Fraction of Binary Combinations of Supplementary Cementitious Materials in the Production of Reactive Powder Concrete *Period. Polytech. Civ. Eng.*

[17] Shubbar A A F, Atherton W, Jafer H M, Dulaimi A F and Al-Faluji D 2017 The Development of a New Cementitious Material Produced from Cement and GGBS *The 3rd BUiD Doctoral Research Conference-Faculty of engineering and IT* (BUiD) pp 51–63

[18] Majdi H S, Shubbar A A, Nasr M S, Al-Khafaji Z S, Jafer H, Abdulredha M, Masoodi Z Al, Sadique M and Hashim K 2020 Experimental data on compressive strength and ultrasonic pulse velocity properties of sustainable mortar made with high content of GGBFS and CKD combinations *Data Br.* 31 105961

[19] Shubbar A A, Jafer H, Abdulredha M, Al-Khafaji Z S, Nasr M S, Al Masoodi Z and Sadique M 2020 Properties of cement mortar incorporated high volume fraction of GGBFS and CKD from 1 day to 550 days *J. Build. Eng.* 30 101327

[20] Shubbar A A, Jafer H, Dulaimi A, Hashim K, Atherton W and Sadique M 2018 The development of a low carbon binder produced from the ternary blending of cement, ground granulated blast furnace slag and high calcium fly ash: an experimental and statistical approach *Contr. Build. Mater.* 187 1051–60

[21] Nayel I H, Burhan S K and Nasr M S 2018 Characterisation of prepared rice husk ash and its effects on strength development in recycled aggregate concrete *IOP Conference Series: Materials Science and Engineering* vol 433 (IOP Publishing) p 12009

[22] Shubbar A A, Sadique M, Nasr M S, Al-Khafaji Z S and Hashim K S 2020 The impact of grinding time on properties of cement mortar incorporated high volume waste paper sludge ash *Karbala Int. J. Mod. Sci.* 6

[23] Kubbah H Z, Nasr M S, Al-Abdaly N M, Dhahir M K and Najim W N 2020 Influence of Incinerated and Non-Incinerated waste paper on Properties of Cement Mortar *IOP Conference Series: Materials Science and Engineering* vol 671 (IOP Publishing) p 12113

[24] Jafer H, Jawad I, Majeed Z and Shubbar A 2021 The development of an ecofriendly binder containing high volume of cement replacement by incorporating two by-product materials for the use in soil stabilization *Sci. Rev. Eng. Environ. Sci.* 30

[25] Al Hawesah H, Shubbar A and Al Mufti R L 2018 Non-destructive assessment of early age mortar containing stainless steel powder *Proceedings of the LJMU 17th Annual International Conference on: Asphalt, Pavement Engineering and Infrastructure* (Liverpool, UK: LIVERPOOL CENTRE FOR MATERIALS TECHNOLOGY)

[26] Nasr M S, Salih S A and Hassan M S 2016 Some Durability Characteristics of Micro Silica and Nano Silica Contained Concrete *J. Babylon Univ. Sci.* 24 980–90

[27] Hassan M S, Salih S A and Nasr M S 2016 Pozzolanic Activity and Compressive Strength of Concrete Incorporated nano/micro Silica *Eng. Technol. J.* 34 483–96

[28] Gopinath S, Mouli P C, Murthy A R, Iyer N R and Maheswaran S 2012 Effect of nano silica on mechanical properties and durability of normal strength concrete *Arch. Civ. Eng.* 58 433–44

[29] Moslemi A M, Khosravi A, Izadinia M and Heydari M 2014 Application of nano silica in concrete for enhanced resistance against sulfate attack *Advanced Materials Research* vol 829 (Trans Tech Publ) pp 874–8
[30] Nasution A, Imran I and Abdullah M 2015 Improvement of concrete durability by nanomaterials Procedia Eng. 125 608–12
[31] Iraqi Standard NO.5 1984 Portland Cement (Central Organization for Standardization and Quality Control, Baghdad, Iraq)
[32] Iraqi Standard NO.45 1980 Aggregate from Natural Sources for Concrete and Building Construction (Central Organization for Standardization and Quality Control, Baghdad, Iraq)
[33] BS 1881: Part 116 1881 Method for determination of compressive strength of concrete cubes (British Standards Institution, UK)
[34] Zhang Z, Jin X and Luo W 2019 Long-term behaviors of concrete under low-concentration sulfate attack subjected to natural variation of environmental climate conditions Cem. Concr. Res. 116 217–30
[35] Liu P, Chen Y, Yu Z and Lu Z 2019 Effect of sulfate solution concentration on the deterioration mechanism and physical properties of concrete Constr. Build. Mater. 227 116641
[36] Oymael S 2008 Effects of Mgso4 and Na2so4 solutions on concrete mortars from cement types Pkc 32.5 and Pc 42.5 Eng. Sci. 3 347–59
[37] Amin M and Bassuoni M T 2018 Performance of concrete with blended binders in ammonium-sulphate solution J. Sustain. Cem. Mater. 7 15–37
[38] Shanbara H K, Shubbar A, Ruddock F and Atherton W 2020 Characterizing the Rutting Behaviour of Reinforced Cold Mix Asphalt with Natural and Synthetic Fibres Using Finite Element Analysis Advances in Structural Engineering and Rehabilitation (Springer) pp 221–7
[39] Al-Rifaie A, Al-Husainy A S and Shanbara H K 2020 Numerical study on the behaviour of end-plate beam-to-column connections under lateral impact loading Int. J. Struct. Eng. 10 150–73
[40] Shanbara H K, Ruddock F and Atherton W 2017 Improving the Mechanical Properties of Cold Mix Asphalt Mixtures Reinforced by Natural and Synthetic Fibers International Conference on Highway Pavements & airfield Technology pp 102–11
[41] Ali I M, Naje A S and Nasr M S 2020 Eco-Friendly Chopped Tire Rubber as Reinforcements in Fly Ash Based Geopolymer Concrete Glob. NEST J. 22 342–7
[42] Ali I M, Nasr M S and Naje A S 2020 Enhancement of cured cement using environmental waste: particleboards incorporating nano slag Open Eng. 10 273–81
[43] Abeer S Z, Hasan Z A and Abdulridha S Q 2020 Investigation some properties of recycled lightweight concrete blocks as a fine aggregate in mortar under elevated temperature Period. Eng. Nat. Sci. 8 400–12
[44] Al Khafaji Z S and Ruddock F 2018 Study the retardant effect of using different sugar’s types on setting time and temperature of cement paste Int. J. Civ. Eng. Technol. 9 519–30
[45] Nasr M S, Hasan Z A and Abed M K 2019 Mechanical properties Of Cement Mortar Made with Black Tea Waste Ash as a Partial Replacement of Cement Eng. Technol. J. 37 45–8
[46] Nayel I H, Nasr M S and Abdulridha S Q 2020 Impact of elevated temperature on the mechanical properties of cement mortar reinforced with rope waste fibres IOP Conference Series: Materials Science and Engineering vol 671 (IOP Publishing) p 12080
[47] Al-Khafaji Z S and Falah M W 2020 Applications of high density concrete in preventing the impact of radiation on human health J Adv Res Dyn Control Syst 12 666–70
[48] Nasr M S, Hussain T H and Najim W N 2018 Properties of cement mortar containing biomass bottom ash and sanitary ceramic wastes as a partial replacement of cement Int. J. Civ. Eng. Technol. 9 153–65
[49] Nasr M S, Ali I M, Hussein A M, Shubbar A A, Kareem Q T and AbdulAmeer A T 2020 Utilization of locally produced waste in the production of sustainable mortar Case Stud. Constr. Mater. e00464
[50] Shubbar A A, Sadique M, Kot P and Atherton W 2019 Future of clay-based construction materials–A review Constr. Build. Mater. 210 172–87
[51] Abdulredha M, Abdulridha A, Shubbar A A, Alkhaddar R, Kot P and Jordan D 2020
Estimating municipal solid waste generation from service processions during the Ashura religious event IOP Conference Series: Materials Science and Engineering vol 671 (IOP Publishing) p 12075

[52] Abdulraheem F S, Al-Khafaji Z S, Hashim K S, Muradov M, Kot P and Shubbar A A 2020 Natural filtration unit for removal of heavy metals from water IOP Conference Series: Materials Science and Engineering vol 888 (IOP Publishing) p 12034

[53] Mohammed A-H, Hussein A H, Yeboah D, Al Khaddar R, Abdulhadi B, Shubbar A A and Hashim K S 2020 Electrochemical removal of nitrate from wastewater IOP Conference Series: Materials Science and Engineering vol 888 (IOP Publishing) p 12037

[54] Alenezi A K, Hasan H A, Hashim K S, Amoako-Attah J, Gkantou M, Muradov M, Kot P and Abdulhadi B 2020 Zeolite-assisted electrocoagulation for remediation of phosphate from calcium-phosphate solution IOP Conference Series: Materials Science and Engineering vol 888 (IOP Publishing) p 12031

[55] Al-Marri S, AlQuzweeni S S, Hashim K S, AlKhaddar R, Kot P, AlKizwini R S, Zubaidi S L and Al-Khafaji Z S 2020 Ultrasonic-Electrocoagulation method for nitrate removal from water IOP Conference Series: Materials Science and Engineering vol 888 (IOP Publishing) p 12073

[56] Shubbar A A F, Alwan H, Phur E Y, McLoughlin J and Al-khaykan A 2017 Studying the Structural Behaviour of RC Beams with Circular Openings of Different Sizes and Locations Using FE Method Int. J. Civil, Environ. Struct. Constr. Archit. Eng. 11 849–52