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EFFECT OF NANOMATERIALS IN CEMENT MORTAR CHARACTERISTICS

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Abstract

Concrete is considered as brittle materials and widely used due to high compressive strength but unfortunately having and has low tensile strength that has a numerous negative impacts on the lifespan of concrete made structures. Therefore, mechanical properties of cement mortar have been investigated experimentally using different types and ratios of nano material to improve the properties. Since the strength of the concrete is of high importance, different materials have been used to enhance the compressive and the tensile characteristics of the cement mortar compressive and tensile strength. Mainly, this objective has been implemented through using micro cement, micro sand, nano silica, and nano clay in developing a nano-cement mortar which can to improve the concrete for the constructional applications. The samples were prepared and tested under tensile and compressive mode according to ASTM-2011 regulations for concrete. The parameters that are taken consideration during the investigation were micro sand, micro cement, nano silica, developed nano clay, and naphthalene sulphonate as super- plasticizers. In general, it has been observed that the results showed a significant increase in both compressive and tensile strength of the mortar at early stages of hardening, where a maximum increase of 22% in the compressive strength was achieved , whereas 3.7 time increase in the compressive strength was recorded over the tradition levels of the concrete strength.

Keywords: Nanomaterial, Mechanical properties, Cement mortar.

1. Introduction

Concrete and steel are considered as most influential materials in the construction industry sector. It is estimated that more than 3 billion tonnes of cement were produced around the world in the past few years which reflects the growing demand in emerging economies in developing countries.

Nomenclatures

c	Cement
D_a	Period in days
F_{cu}	Predicted compressive strength, MPa
f_{cu}	Measured compressive strength, MPa
f_t	Tensile strength, MPa
w	Water

Abbreviations

ASTM	American Society for Testing and Materials
CNF	Carbon Nano Fiber
CNT	Carbon Nano Tube
NSCSC	Nano Sand Cement Silica fum Clay

As a matter of fact, cement manufacture is an energy intensive process and represents 7% of worldwide energy consumption and 4% of worldwide industrial CO_2 emissions. Therefore, nanomaterials when it is used to enhance the properties can improve durability, structural efficiency and strength of cementitious materials. Accordingly, can assist in improving the quality and he lifetime of the structures. The use of nanomaterials with cement can reduce carbon dioxide emissions associated with concrete production [1, 2]. However, nano materials are gaining widespread attention to be used in construction sector so as to exhibit enhanced performance of materials in terms of smart functions and sustainable features. The literature showed that the use of nanomaterial in cementitious system is mainly due to the fact that concrete remains the most complex material and its hydration mechanism is still not completely understood. Therefore, investigators and researchers have been focusing on the substantial scientific background of this essential material at nano level.

Furthermore, continuous efforts have been done to improve the durability and the sustainability of concrete, and they have realized significant increment in mechanical properties of cementitious materials by using nano-materials [3, 4]. On the other hand, the use of nanoscale industrial waste-based cement replacements can reduce carbon dioxide emissions associated with concrete production [5]. The addition of some metal oxide nanoparticles to concretes can both reduce the permeability of concrete to ions and increase the strength of concrete, thereby improving durability. The addition of TiO_2 nanoparticles [6], Al_2O_3 nanoparticles [6], ZrO_2 nanoparticles [8], Fe_2O_3 nanoparticles [9], SiO_2 nanoparticles [10] and metal oxide containing nano clays [11] have all been shown to improve concrete and/or cement mortar properties. Properties of the cement-based composites made from the CNTs/CNFs-grown cement/mineral admixture were presented. Experimentally, Li et al, [12] studied the mechanical properties of nano-Fe_2O_3 and nano-SiO_2 cement mortars. The 56-day pore structures of the cement mortars produced by the addition of silica fume and nano-SiO_2 (NS), nano-Al_2O_3 (NA) and nano-Fe_2O_3 (NF) powders. Basically, singular, binary or ternary combinations at different proportions of the binder content were investigated through MIP and BET analysis [13].

Metal oxide nanoparticle addition accelerates reactions during initial hydration thus strengthening cement composites. The metal oxide nanoparticles react with

CaOH increasing the amount of calcium silicate hydrate (C-S-H) produced, leading to a more compact microstructure. By this means not only decreasing permeability but also improving mechanical properties [14] such as compressive strength, flexural strength and abrasion resistance [15]. The flexural strength of a very thin ferrocement element, by using NSCSC mortar as a replacement to the normal cement mortar, usually used in ferrocement elements was examined. The measured results showed an increase the flexural strength of a very thin ferrocement using NSCSC mortar [16]. Zhang and Li [17] found that the addition of 1% by weight of binder of 15 nm diameter TiO_2 to concrete refined the pore structure and increased the resistance to chloride penetration by 31%. Shekari and Razzaghi [18] found that the addition of 1.5% (by weight of cement-based material) of 10–25 nm ZrO_2, TiO_2, Al_2O_3 or Fe_3O_4 increased the compressive strength and reduced chloride penetration of the concrete by 20–80% respectively. Through-depth cracks, of course, severely compromise improvements in impermeability. Oscar et al. [19] studied the effect of the reagglomeration process of Multi-Walled Carbon Nanotubes (MWCNT) dispersions on the activity of silica nanoparticles at early ages when they are combined in cement matrixes. MWCNT/water/superplasticizer dispersions were produced via sonication and combined with nano silica particles in the mixing water of the cement samples. The methods and theories of in situ growth of CNTs/CNFs on cement/mineral admixture, including chemical vapour deposition method and microwave irradiating conductive polymers method, were summarized [20]. The addition of SiO_2 nanoparticles is widely reported to be effective for strengthening concrete; both normally vibrated concrete and self-compacting concrete [21].

Al-Rifaie et al. [22] examined the compressive and flexural strength of nano cement mortar by using micro cement, micro sand, nano silica, and nano clay in developing a nano cement mortar which can lead to improvements in ferrocement construction. In addition, the influence of heating on compressive strength of cement mortar, whereas ferrocement eco-housing system was able to produce very energy efficient dwellings [23]. Nazari and Riahi [24] reported that the compressive, split tensile and flexural strength of the 4 wt.% SiO_2 nanoparticle concrete is, 1.7, 2.2 and 1.6 respectively times greater than that of the equivalent SiO_2 nanoparticle free concrete after 28 days of curing. Generally, cement-based materials containing SiO_2 nanoparticles are stronger than those containing SiO_2 fume [25]. This is attributed to the accelerated cement hydration, increased pozzolanic activity, reduced pore size and improved interfacial bonding between the hardened cement paste and aggregate that is associated with the decreased average particle size of the SiO_2 [26]. The effect of elevated temperatures on chemical composition, microstructure and mechanical properties of high strength mortars with nano alumina was investigated [27]. Effect of nano clay particles on mechanical, thermal and physical behaviours of waste-glass cement mortars was investigated [28]. The compressive strengths and the microstructure photographs of cement mortars containing nanosilica with various sizes compared with cement mortar with silica fume was investigated by Sattawat et al. [29]. Finite element method was used to investigate the impact of inclusion in hypothetical nano composite [30], cracked nano composite [31], debonding between the nanofiber and the matrix [32], pre-crack existence in nanocomposite [33] as well as studying the impact of the mismatch properties [34]. Moreover, FEA has been used to investigate the effect of the nanoinclusion [35], interfacial debonding defects [36], interfacial defects [37] and fractured particulate composite [38] on the characteristics and failure of the nano composite, whereas the development of nano structural element called “nano-polymercement” which can be used for different applications [39].

The authors presented a research work to examine the mechanical properties of nano particles in developing a nano cement mortar which can lead to improvements in the performance of ferrocement to be the replacement to the materials needed, for example, strengthening or rehabilitation of pipe lines for pressurized pipes rather than using polymeric composite materials, construct poles for lighting and wind turbine, manufacturing under water turbine blades and even impellers, and bullet proof protective panels or even anti explosion sheets used in trucks [40-42].

2. Sample Preparation

Cubes and prisms were cast and tested for determining the compressive and tensile strengths. The parameters considered during the investigation were micro sand, micro cement, nano silica, naphthalene sulphonate, nano clay and the chemical compositions of micro cement. Besides, the nano silica, the develop nano clay and the general specifications of naphthalene sulphonate are carried out. In the present work, compressive and tensile strength of the developed nano cement mortar will be investigated.

3. Materials Properties

The material used in this investigation is described in this section, which contains the chemical and the physical properties of the cement used, the chemical composition of the nano-silica and the developed nano-clay, as well as the properties of the naphthalene sulphonate.

Cement: Micro Portland cement sulphate resistance, conforming ASTM C150 type II, particle size (45- 0.7) µm, the chemical and physical compositions are given in Tables 1 and 2.

Sand: Micro sand (finer than 75 µm), conforming ASTM C33.

Silica: Nano silica (500-40) µm, the chemical composition is given in Table 3.

Clay: Developed nano clay (200-3) µm. Table 4 elucidates the chemical composition obtained by burning the clay up to 700^{o}C.

Naphthalene sulphonate: used as super-plasticizers, high range (i.e., 88%) water reducing according to ASTM C494. Table 5 shows a Naphthalene Sulphonate specification.

Table 1. Chemical composition of cement considered in the present investigation.

Item	Used Cement
C_3A, max%	2.0
Sulfur trioxide (SO_3), max%	0.95
Loss on ignition, max%	0.92
Insoluberesidue, max%	0.71

Table 2. Physical composition of cement considered in the present investigation.

Used cement	Standard	Item
Air content of mortar, volume %		
Max.	12.0	-
Min.	-	-
Fineness, specific surface m^2 /kg (alternative methods):		
Turbidimetertest, min.	160	
Air permeability test, min.	280	298
Autoclave expansion, max.%	0.8	
Strength, not less than the values shown for the ages indicated as follows		
Compression strength, MPa		
3 days	15	19
Time of setting (alternative methods)		
Vicat test		
Time of setting min., not less than	45	53
Time of setting min., not more than	375	488

Table 3. Chemical composition in nano silica.

Chemical composition	Contents %
Silicon dioxide, SiO_2	94.3
Aluminum oxide, Al_2O_3	0.06
Ferric oxide, Fe_2O_3	0.46
Calcium oxide, CaO	0.51
Titania	2.31
Loss on Ignition	2.25

Table 4. Developed nano clay specification.

Chemical composition	Contents %
Silicon dioxide, SiO_2	49.87
Aluminum oxide, Al_2O_3	32.11
Ferric oxide, Fe_2O_3	8.78
Calcium oxide, CaO	0.34
Titania	1.45
MgO	0.28
K_2O	0.81
Na_2O	0.77
Loss on Ignition	0.66

Table 5. Naphthalene sulphonate specifications.

Color	Brown
Density	1.12-1.14 kg/liter
Chloride content % (EN480-10)	Less than 0.1
Alkaline content % (EN480-12)	Less than 10

4. Testing Procedures

The experimental procedure was carried out to investigate the tensile and the compressive strength of the mortar based on testing different combination of sand/cement ratios as well as to the other additives. Therefore the tested samples are classified into four groups according to the mixture properties. The mortar matrices considered during the present investigation may be summarized in the following groups:

- Group (A): Sand/cement ratio 1/ 1, 1.5/1, 2/ 1, 2.5/1, 3/1, with w: c ratio = 0.4.
- Group (B): Sand/cement ratio 1/ 1, 1.5/1, 2/ 1, 2.5/1, 3/1, each with 10% of nano silica, and 1.4% naphthalene sulphonate, w: c ratio = 0.34.
- Group (C): Sand/cement ratio 1/ 1, 1.5/1, 2/ 1, 2.5/1, 3/1, each with, 18% nano clay, and 1.4% naphthalene sulphonate, w: c ratio = 0.34.
- Group (D): Sand/ cement ratio 1/ 1, 1.5/1, 2/ 1, 2.5/1, 3/1, each with, 18% nano clay, 10% nano silica and 1.4% naphthalene sulphonate, w: c ratio = 0.34.

On the other hand, the experimental set up for the four groups samples were tested based on ASTM-2011 regulation and after the curing period, which can be summarized as:

1) Compressive strength at age of 28 curing days were carried out, where sixty 50mm mortar cube specimens with the above mortar groups (A, B, C, D) were performed after 28 curing days on 250 kN machine according to ASTM-C 109/C 109M-11.
2) Tensile strength at 28 curing days were carried out, where sixty 50mm cube specimens with mortar group (D) were performed after 28 curing days.

5. Results and Discussion

In general, the results of the experimental tests were collected and organized based on the tested groups to illustrate the impact of the additives as well as the nano materials on the mechanical properties of the mortar. However, the outcomes of compression and tension tests after 28 curing days. The results are represented in Figs. 1 and 2. It may be noted that each of the above compressive strength and tension strength values is the mean of six cubes.

It is illustrated from Fig. 1 that the highest value of compressive and tensile strength of nano cement mortar of all four developed cement mortar groups, i.e., (A, B, C, D) after 28 curing days can be achieved by sand/ cement ratio of 1.5.

The investigation of Al-Rifaie et al. was concluded that the developed nano cement mortar of group (D) can achieve more than 15% of its final compressive strength in one day and more than 60% in fourteen days (normally the final strength of concrete can be achieved in 120 days). The behaviour at early ages gains importance in precast structures as the case with most of ferrocement structures when submitted to early stresses due to transportation and erection operations [22]. It was seen that the developed nano mortar of group (D) can achieve more than 40% of compressive strength in one day in comparison with nano cement mortar with mortar matrix group A and the compressive strength in 3 days is more than 60% of the compressive strength of group (A) with 28 curing days and the compressive strength in 7 days is greater than the compressive strength of group (A) with 28 curing days. It was also concluded that the compressive strength values of cement mortar group (D) beyond age 120 curing days do not change, and this means that the dehydration is completed. In addition, a formula for estimating the cube compressive strength, in terms of days, was proposed as follows [22]:

$$F_{cu} = 27.01 * \ln(Da) + 13.642 \ (MPa) \quad (1)$$

where, *Da* is the period in days.

Now, by using the measured values of tensile strength tabulated in Table 6 and by using the regression technique, the following expression is proposed:

$$f_t = 0.2426 f_{cu} - 2.3339 \quad (2)$$

where, f_t is the tensile strength, MPa, f_{cu} is the measured compressive strength, MPa.

However, a comparison between the measured values of group (D) and the values obtained using the proposed Eq. (1) to determine the tensile strength are shown in Table 6.

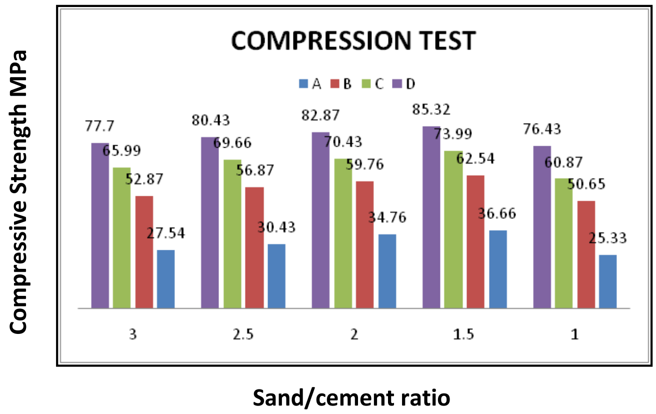

Fig. 1. Compressive strength MPa vs. micro sand: micro cement ratio.

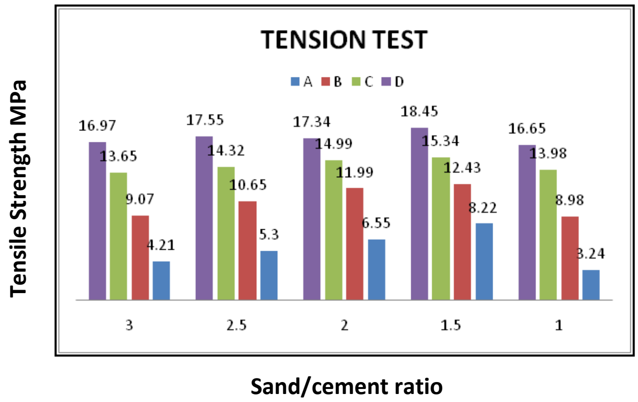

Fig. 2. Tensile strength MPa vs. micro sand: micro cement ratio.

Table 6. Comparison between the measured values of tensile strength tabulated in Table 6 and the values obtained using the proposed Eq. (1).

Group	Sand/ cement ratio	Measured tensile strength, MPa	Tensile Strength, Expression (1)	Measured Tensile Strength/ Expression (2)
A	1	3.24	3.81	0.85
	1.5	8.22	6.56	1.25
	2	6.55	6.10	1.07
	2.5	5.3	5.05	1.05
	3	4.21	4.35	0.97
B	1	8.98	9.95	0.90
	1.5	12.43	12.84	0.97
	2	11.99	12.16	0.98
	2.5	10.65	11.46	0.93
	3	9.07	10.49	0.86
C	1	13.98	12.43	1.12
	1.5	15.34	15.62	0.98
	2	14.99	14.75	1.02
	2.5	14.32	14.57	0.98
	3	13.65	13.68	0.99
D	1	16.65	16.21	1.03
	1.5	18.45	18.36	1.01
	2	17.34	17.77	0.98
	2.5	17.55	17.18	1.02
	3	16.97	16.52	1.03

It is clearly observed from Table 6 and Figs. 1 and 2, that it may be concluded that the compressive strength of nano cement mortar of group (D) is higher than the tensile strength by 4.62, i.e., (Tensile strength = Compressive strength /4.62).

According to ASTM: C 109 [43], tests were carried out to measure the compressive and tensile strength of ordinary sand: cement mortar 3:1 with water: cement ratio of 0.4 and the size of sand particles is smaller than 0.85 mm and bigger than 0.6 mm.

As a result of the present practical investigation, it was concluded that there is a significant increase in both tensile and compressive strength of the mortar due to different reasons, like nano-material uses as well as the sand/cement ratio. In general it is important to express the outcomes of the results to be shown in particle way, since the aim of the investigation to develop a material to be used by end user in the constructional applications. Therefore, the tensile strength of the developed mortar can be related to the compressive strength, which can be represented to be compressive strength/10 as elucidated from the results, which represents the highest ratio estimated. Moreover, while the corresponding tensile strength value using micro cement-micro sand mortar of group (A), where the sand/ cement ratio of 3:1 was used, the tensile strength of this can be linked to the compressive strength through a factor of 1/7.82 of the compressive strength. Eventually, considering nano cement mortar of group (D) with micro sand: micro cement of 3:1, the value of tensile strength can be expresses as tensile strength = compressive strength/ 4.58, which shows the lowest ratio observed through the study.

6. Conclusions

Cement mortar was experimentally investigated to enhance the mechanical properties, especially tensile and the compressive strength due to the fact that the strength of the concrete is of high importance to constructional applications. The study was accomplished through adopting different types of nano-material and mixing and ratios to figure out the impact of these additives on the improvement or depreciation of the mortar. In general, the present study showed that there is an improvement in the mechanical properties of nano cement mortar as developed in the present work which was experimentally investigated. This can be attributed to many factors, like mixing ratio as well as the type of the nano-materials used.

Some conclusions and future work is drawn based on the current investigation. It has been clearly evidence that the developed nano cement mortar matrix of sand/ cement ratio of 1.5/1, with 18% nano clay, 10% nano silica and 1.4% naphthalene sulphonate, w: c ratio = 0.34 showed that the experimental outcome of the compressive strength of 85.32 MPa, and tensile strength of 18.45 MPa that was for the 28 days curing time. These levels of the strength is considered as higher than the strength of the reference nano cement mortar as developed in the present work which has sand/ cement ratio of 1.5/1 with w: c ratio = 0.4 by the ratio of 2.33 and 2.25 respectively. In this context, it has been recognized that the measured results displayed an increase in tensile strength in comparison with compressive strength of the developed nano cement mortar.

Besides, the experimental results revealed that the tensile strength levels of the developed nano cement mortar of the present work ranging between (0.0446-0.0762) of the compressive strength value. A consequence of the fact that by comparing the plain cement mortar which usually used in the production of the mortar, especially for the manufacturing ferrocement elements, with the cement mortar mixed with the micro/or nano particles, it was obviously noticed that in a supreme mechanical performance of the cement mortars with nano particles. Finally, a helpful empirical expression to predict the tensile strengths was proposed for the estimation purposes which could be determined the tensile and the compressive strengths approximately.

References

1. Hanus, M.J.; and Harris, A.T. (2013). Nanotechnology innovations for the construction industry. *Progress in Materials Science*, 58, 1056-1102.
2. Pacheco-Torgal, F.; and Jalali, S. (2011). Nanotechnology: Advantages and drawbacks in the field of construction and building materials. *Construction and Building Materials*, 25, 582-590.
3. Singh, L.P.; Karade, S.R.; Bhattacharyya, S.K.; Yousuf, M.M.; and Ahalawat, S. (2013). Beneficial role of nanosilica in cement based materials - A review. *Construction and Building Materials*, 47, 1069-1077.

4. Lebental, B.; Chainais, P.; Chenevier, P.; Chevalier, N.; Delevoye, E.; and Fabbri, J.M. (2011). Aligned carbon nanotube based ultrasonic microtransducers for durability monitoring in civil engineering. *Nanotechnology*, 22, 395-501.
5. Broekhuizen, P.; Broekhuizen, F.; Cornlissen, R.; and Reijnders, L. (2011). Use of nanomaterials in the European construction industry and some occupational health aspects thereof. *Journal of Nanoparticle Research*, 13, 447-62.
6. Nazari, A.; and Riahi, S. (2011). TiO_2 nanoparticle effects on physical, thermal and mechanical properties of self-compacting concrete with ground granulated blast furnace slag as binder. *Energy and Buildings*, 43(4), 995-1002.
7. Nazari, A.; and Riahi, S. (2011). Improvement compressive strength of concrete in different curing media by Al_2O_3 nanoparticles. *Material Science and Engineering: A*, 528(3), 1183-1191.
8. Hekari, A.H.; and Razzaghi, M.S. (2011). Influence of nano particles on durability and mechanical properties of high performance concrete. *Procedia Engineering*, 14, 3036-41.
9. Li, H.; Xiao, H.G.; and Ou, J. (2004). A study on mechanical and pressure-sensitive properties of cement mortar with nanophase materials. *Cement and Concrete Research*, 34, 435-438.
10. Senff, L.; Hotza, D.; Lucas, S.; Ferreira, V.M.; and Labrincha, J.A. (2012). Effect of nano-SiO_2 and nano-TiO_2 addition on the rheological behavior and the hardened properties of cement mortars. *Material Science and Engineering: A*, 532, 354-356.
11. Kuo, W.Y.; Huang, J.S.; and Yu, B.Y. (2011). Evaluation of strengthening through stress relaxation testing of organo-modified montmorillonite reinforced cement mortars. *Construction and Building Materials*, 25, 2771-2776.
12. Xiao, H.; Gang, H.; Jie, Y., and Jinping, O. (2004). Microstructure of cement mortar with nano-particles, *Composites: Part B*, 35, 185-189.
13. Meral, O.; and Remzi, S. (2014). Pore structure analysis of hardened cement mortars containing silica fume and different nano-powders. *Construction and Building Materials*, 53, 658-664.
14. Senff, L.; Hotza; D., Lucas, S.; Ferreira, V.M.; and Labrincha, J.A. (2012). Effect of nano-SiO_2 and nano-TiO_2 addition on the rheological behavior and the hardened properties of cement mortars. Influence of nano particles on durability and mechanical properties of high performance concrete, 532, 354-361.
15. Chen, L.; and Lin, D.F. (2009). Applications of sewage sludge ash and nano-SiO_2 to manufacture tile and construction material. *Construction and Building Materials*, 23, 3312-20.
16. Al-Rifaie, W.N.; Ahmed, W.K.; and Mohanad, M.O. (2012). Performance of Ferrocement Using NSCSC Mortar. *NuRER 2012-Proceedings of the 3rd International Conference on Nuclear & Renewable Energy Resources*. İstanbul, Turkey.
17. Zhang, M.H.; and Li, H. (2011). Pore structure and chloride permeability of concrete containing nano-particles for pavement. *Construction and Building Materials*, 25, 608-16.

18. Shekari, A.H.; and Razzaghi, M.S. (2011). Influence of nano particles on durability and mechanical properties of high performance concrete. *Procedia Engineering*, 14, 3036-3041.
19. Oscar, M.; Germán, S.; and Jorge, T. (2014). Effect of the reagglomeration process of multi-walled carbon nanotubes dispersions on the early activity of nanosilica in cement composites. *Construction and Building Materials*, 54, 550-557.
20. Shengwei, S.; Xun, Y.; Baoguo, H.; and Jinping, O. (2013). In situ growth of carbon nanotubes/carbon nanofibers on cement/mineral admixture particles: A review. *Construction and Building Materials*, 49, 835-840.
21. Jo, B.W.; Kim C.H.; and Lim, J.H. (2007). Characteristics of cement mortar with nano-SiO_2 particles. *ACI Materials Journal*, 104, 404-407.
22. Al-Rifaie, W.N.; Mohanad, M.O.; and Ahmed, W.K. (2013). Development of Nanocement Mortar as a Construction Material. *Advanced Materials Research*, 795, 684-691.
23. Al-Rifaie, W.N.; Ahmed, W.K.; Ibraheem, L.E.; and Al-Samarraie, H.Y. (2014). Ferrocement in Eco-Housing System. *International Journal of Renewable Energy Research*, 4(1), 151-158.
24. Nazari, A.; and Riahi, S. (2011). The effects of SiO_2 nanoparticles on physical and mechanical properties of high strength compacting concrete. *Compos Part B-Eng*., 42, 570-578.
25. Jo, B.W.; Kim, C.H.; and Lim, J.H. (2007). Characteristics of cement mortar with nano-SiO_2 particles. *ACI Materials Journal*, 104, 404-7.
26. Zhang, M.H.; and Islam, J. (2012). Use of nano-silica to reduce setting time and increase early strength of concretes with high volumes of fly ash or slag. *Construction and Building Materials*, 29, 573-580.
27. Nima, F.; Abang, A.; Abang, A., Ramazan, D.; and Parvez, A.M. (2013). Effect of halloysite nanoclay on mechanical properties, thermal behavior and microstructure of cement mortars. *Cement and Concrete Research*, 48, 97-104.
28. Aly, M.; Hashmi, M.S.J.; Olabi, A.G.; Messeiry, M.; and Hussain, A.I., Effect of nano clay particles on mechanical, thermal and physical behaviours of waste-glass cement mortars. *Materials Science and Engineering A*, 528, 7991-7998.
29. Sattawat, H.; Tawich, P.; and Somchai, C. (2014). Effect of the particle size of nanosilica on the compressive strength and the optimum replacement content of cement mortar containing nano-SiO_2. *Construction and Building Materials*, 50, 471-477.
30. Ahmed, W.K.; Omar, F.K.; and Haik, Y. (2007). The effect of nano-circular inclusion on the interfacial stresses of nano-composite. *First Sharjah International Conference on Nanotechnology and Its Application*. Sharjah, UAE.
31. Ahmed, W.K.; Al-Douri, Y.; and Kubilay, A. (2012). Finite element analysis of cracked nano-fiber reinforced composite. *Proceedings of the 6th European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS 2012)*. Vienna University of Technology, Vienna, Austria.
32. Ahmed, W.K. (2013). The influence of debonding on the mechanical properties of hybrid nanocomposites. *Proceedings of the 4th International*

Conference on Metamaterials, Photonic Crystals and Plasmonics META'13. Sharjah, United Arab Emirates.

33. Ahmed, W.K.; Kubilay, A.; and Al-Doury, Y. (2013). Failure of pre-cracked nano-composite. *Journal of Nanostructured Polymers and Nanocomposites*, 9, 59-66.
34. Ahmed, W.K.; and Shakir, S.A. (2014). The impact of a mismatch on the interfacial stresses in nanocomposite. *The International Journal of Nanoelectronics and Materials*, 7(2), 157-166.
35. Ahmed, W.K.; and Al-Rifaie, W.N. (2013). The impact of embedded nanoinclusion in nanofiber reinforced composite. *Physical Review & Research International*, 3, 438-451.
36. Ahmed, W.K. (2013). Investigating impact of the interfacial debonding on the mechanical properties of nanofiber reinforced composites. *Journal of Nano- and Electronic Physics*, 5, 04059-1 - 04059-5.
37. Ahmed, W.K. (2013). The role of nanofiber/matrix interface defects on the failure of nanocomposite comparative study. *Nano Trends: A Journal of Nanotechnology and Its Applications*, 15, 63-71.
38. Ahmed, W.K.; and Teng, H. (2014). Characterization of fractured particulate reinforced composite. *International Journal of Microstructure and Materials Properties*, 9(2), 160-175.
39. Al-Rifaie, W.N.; Ahmed, W.K.; and Mahdi, O.M. (2014). Experimental investigation of nano-polymercement composite. *Study of Civil Engineering and Architecture*, 3, 29-35.
40. IFS Committees 10, Ferrocement Model Code (2001). *Building code recommendations for ferrocement*. (IFS 10-01).
41. ACI Publication SP.61 (1979). *Ferrocement–materials and applications*, 1-195.
42. ACI committee 549 (1980). Guide for the design, construction, and repair of ferrocement. *ACI Structural Journal*, May-June, 325-351.
43. ASTM C 109/C109 (2011). M-11. *Standard test method for compressive strength of hydraulic cement mortars* (Using 2 – in. or [50 mm] Cube Specimens), 04.01, 79-87.