Investigation on the Performance Characteristics of Concrete Incorporating Nanoparticles

Revathy Jayaseelan [1]***, Gajalakshmi Pandalu*** [2] ***and Sanju Selvam*** [3]

[1] Professor, B. S. Abdur Rahman Crescent University, India.
E-Mail: revathyj@bsauniv.ac.in
[2] Associate Professor, B. S. Abdur Rahman Crescent University, India.
E-Mail: gajalakshmi@bsauniv.ac.in
[3] B. S. Abdur Rahman Crescent University, India.

ABSTRACT

Durability of concrete structures is one of the foremost concerns in construction industry. This research work explored the development and performance characteristics of concrete incorporating nanoparticles. The study focuses on the effective utilization of nanoparticles with different dosage amounts of 0.5 %, 1% and 1.5% added to the weight of binder (cement + metakaolin) materials. In addition, metakaolin is partially added to cement to enhance the sustainability of concrete. The performance characteristics investigated included compressive strength, water absorption, sorpitivity and chloride ion penetrability. Based on the investigations, it is found that a combination of nano-SiO_2 and nano-Fe_2O_3 enhanced compressive strength of concrete.

From the results of water absorption test, the higher content of nano-Fe_2O_3 and nano-SiO_2 showed a sharp drop of about 54.16% and 35.83%, respectively. The sorptivity coefficient decreased by 43.33% and 69.01% corresponding to 1.5% addition of nano-Fe_2O_3 and nano-SiO_2 with reference to the control group. The reason is due to densified micro-structure and refined pores. NSF group specimens indicate about 64.17% reduction in water penetration with respect to control group mixture. A lower chloride ion charge passage is noticed in NF3 and NS3 specimens of about 35.97% and 56.09%, respectively, compared with that of the control specimen. A considerable amount of reduction of about 64.17% and 73.33% is observed, respectively, for water absorption test and sorptivity coefficient test. A remarkable correlation is observed between the strength (compressive) and durability indices of concrete of various groups. Thus, nanoparticles added to concrete improve the durability of concrete and provide an effective solution for a better sustainable environment.

KEYWORDS: Durability, Chloride ion penetrability, Compressive strength, Correlation, Nano-particles, Sorpitivity, Water absorption.

INTRODUCTION

Over a long period of time, the composite material concrete is considered as an essential building material. For any structure, durability of concrete plays a significant role (Gjorv, 2011). Using normal grade of concrete provides a less durable concrete structure, which necessitates regular inspection and routine maintenance. Now-a-days, construction industry has shown substantial attention to utilizing high-performance concrete. For energy efficiency and reduced CO_2 emissions, supplementary cementitious materials or mineral admixtures including pulverized fuel ash or fly ash, slag from blast furnace and micro-

Received on 29/11/2017.
Accepted for Publication on 27/1/2019.

silica or silica fume are incorporated as a partial replacement of cement. Such replacement has become significant because of its role in concrete durability (Camcho and Afif, 2002). A study to determine the limits for concrete mix design using fly ash replacement of cement in the reinforced concrete pipe manufacturing process was conducted (Berryman et al., 2005). The study revealed that 35% and 25% replacement of class C and class F fly ash, respectively, showed the maximum compressive strength of concrete at the age of 7 days. An investigation was conducted on the mechanical properties of concrete made with ground granulated blast furnace slag subjected to an elevated temperature (Siddique and Kaur, 2012). The study indicated that there was not much significant deterioration of the mechanical properties of concrete between 27°C and 100°C. It was also suggested that ground granulated blast furnace slag could be utilized up to 20% in concrete designed for nuclear structures. The highest replacement level of 40% by fly ash and 16% by silica fume as a combination exhibited a 10% increase in the 28-day compressive strength compared to that of control concrete (Seshasayi et al., 2001). The effect of incorporating metakaolin increases the strength and durability characteristics of concrete (Dinakar et al., 2013). From the test results, it was observed that 10% replacement was the optimum level in terms of compressive strength. Beyond 10% replacement levels, strength was decreased but remained higher than that of the control mixture. A revolutionary performance can be made in concrete through the application of nano-technology (Sobolev et al., 2008). Several research works have been reported on the various types of nanoparticles added into mortar or concrete to investigate their performance properties. Including nano-sized particles in concrete helps speed up the hydration process and densify the micro-structural characteristics of cement matrix, thus paving the way to minimize the permeation activity of concrete (Sanchez and Sobolev, 2010). The improved rheological properties are observed on incorporating nano-scaled SiO_2 particles in cement slurry. The result also shows that the setting time and span of the dormant period are reduced (Choolaei et al., 2012). The pattern of calcium-silicate-hydrate (C-S-H) gel increases due to the combination of pozzolanic action with calcium hydroxide, thereby tending to improve the micro-structure (Jo et al., 2007). The inclusion of nano-$CaCO_3$ helps activate the cement paste. Flowability decreases with the increase in nano-$CaCO_3$ (Liu et al., 2012). The workability of concrete reduces with the inclusion of ZnO_2 particles, but the usage of plasticizers helps improve the performance of workability. The percentage of water absorption in concrete decreases by partial replacement of nano-ZnO_2 particles in cement (Nazari and Shadi, 2011). Nano-SiO_2 particles help in the improvement of micro-structure of concrete and act as an activator to speed up the pozzolanic actions (Scrivener and Kirkpatrick, 2008).

The effect of nano-SiO_2 on a cement paste (Qing et al., 2007) is evaluated along with micro-silica. The strength results revealed that there was an increasing trend of cement paste together with the incorporation of nano-SiO_2. The early-age strength decreased to some extent by increasing the amount of silica content; however, it increased at later ages. At early age, the production of calcium hydroxide increased with the inclusion of nano-SiO_2. It also decreases the apparent density and increases the air content (Senff et al., 2009). The setting time period for cement paste is reduced with the inclusion of nano-Al_2O_3 (Nazari et al., 2010). The photocatalytic degradation of pollutants was also assessed (Senff et al., 2013). An investigation on the effect of binary and ternary combination of nanoparticles in cement mortars was carried out (Oltulu and Sahin, 2011). It demonstrated that more than two combinations of nanoparticles demonstrate an unfavorable effect on the properties of mortar (Mohseni et al., 2015). The main idea of this research is to expand the body of knowledge on the effective utilization of nanoparticles added in concrete which will in turn provide a durable and sustainable built environment. Thus, the present research explores the development and performance characteristics of concrete incorporating nanoparticles. The study also presents the correlation among compressive strength and durability characteristics of nanoparticles added in concrete.

MATERIALS AND METHODS

Materials

In this paper, 53 grade Portland cement as per IS 12269 is used. According to IS 383, the fineness modulus of fine aggregate is 3.07. A size less than 20 mm crushed granite rock is utilized as coarse aggregate. Specific gravity corresponding to fine and coarse aggregates (IS2386) is 2.31 and 2.54, respectively. Metakaolin, a natural pozzolana, is used as a mineral admixture with a specific gravity of 2.5 and a grain size area of 2.54 µm. To adjust the flow property of concrete, polycarboxylate ether-based chemical admixture is employed in this study. Nano-silica (SiO_2) and nano-ferric oxide (Fe_2O_3) are employed in this research. Average particle sizes of 20 nm and 90 nm are used, respectively, for nano-SiO_2 and nano-Fe_2O_3. The corresponding specific surface areas for nano-SiO_2 and nano-Fe_2O_3 are 202 m^2/g and 150 m^2/g.

Concrete Sample Preparation

Totally, four different groups of concrete mixes are prepared. In all the concrete mixes, metakaolin is partially replaced by 15% by weight of cement. CO, the control mixture and NS groups are prepared with nano-SiO_2 particles and NF groups consisting of nano-Fe_2O_3 particles. The concrete mix group NSF is prepared by SiO_2 and Fe_2O_3 nanoparticles.

By conducting some preliminary experimental tests, different amounts of 0.5%, 1% and 1.5% nanoparticles are added to the weight of binder (cement + metakaolin) materials. For the entire concrete mix group, a uniform ratio of water to binder is kept as 0.38. Polycarboxylate ether-based superplasticizer of 1% to the weight of binder materials is used. Table 1 shows the detailed mixture proportions of concrete. For the preparation of nano-modified concrete mixtures, cement, metakaolin, fine and coarse aggregates are mixed for about 2-3 minutes. In 30% of water, polycarboxylate ether-based solution is mixed thoroughly and nanoparticles are added in an appropriate ratio and blended well at a speed of 350 rpm for 5 minutes. More attention should be paid while mixing the nanoparticles. Then, the remaining water is added to the final mixture and blended well for about 3-4 minutes.

Testing Methods

Slump cone test is carried out (IS 1199) in order to assess the fresh concrete property of concrete. Strength and durability tests are performed for hardened concrete specimens as presented in Table 2. The prepared concrete specimens of different sizes (see Table 2) are demoulded and curing is done in water. After the curing age of 28 days, the hardened concrete specimens are tested. Test results in this investigation are averages of three specimens.

Table 1. Concrete mixture proportions

Mix ID	Binder Materials	Nano-SiO_2	Nano-Fe_2O_3	Fine aggregate	Coarse aggregate	Slump
	in (kg/m^3)					(mm)
CO	388	-	-	727	1245	95
NS1	388	1.94	-	727	1245	78
NS2	388	3.88	-	727	1245	79
NS3	388	5.83	-	727	1245	76
NF1	388	-	1.94	727	1245	84
NF2	388	-	3.88	727	1245	81
NF3	388	-	5.83	727	1245	79
NSF	388	1.94	1.94	727	1245	73

Table 2. Specimens and standards for strength and durability tests in concrete

Performance test in hardened concrete	Type of test investigated in concrete specimen	Size of specimens
Strength test	Compressive strength test (IS516)	150 mm x 150 mm x 150 mm
Durability test	Water absorption test (ASTM C642)	Diameter – 100 mm Height – 50 mm
	Water sorptivity test (ASTM C1585)	
	Chloride ion penetrability test (ASTM C1202)	

RESULTS AND DISCUSSION

Slump Test

The slump values for all the concrete groups are presented in Table 1. From the obtained results, it is clear that the slump values for nanoparticles added to concrete are less than that of the control group. This is mainly due to higher fineness of nanoparticles present in the mix, which requires huge water content for wetting its surface. In the nanoparticle-added concrete, the fluidity rate is dropped and the water demand is increased even though superplasticizer is added. It is also observed that the nanoparticle-added concrete is in a workable state.

Compressive Strength Test

Compressive strength of various groups of concrete is depicted in Figure 1. It is well noted that the strength increased as the amount of nanoparticles increased up to 1%. Beyond 1% addition of nano-Fe_2O_3 particles in concrete, the compressive strength dropped, while the compressive strength of 1.5% of nano-Fe_2O_3 particles (NF3) is still higher than that of the control concrete. Figure 1 shows that the inclusion of nano-SiO_2 particles significantly improves the compressive strength of examined concrete specimens. The strength improvement is higher which is directly related to the percentage increase of nano-SiO_2 content. NS3 specimen indicates a substantial increase in compressive strength and this is because of the supplementary development of C-S-H gel. The maximum compressive strength is attained at 1.5% and 1% corresponding to NS and NF groups. This is due to the higher amount of nanoparticles present in the mixture, leading to leaching of excess quantity of silica content, resulting in strength reduction. For NSF group concrete mix, the maximum compressive strength of about 60.1% is attained, which increased more than those of other group specimens.

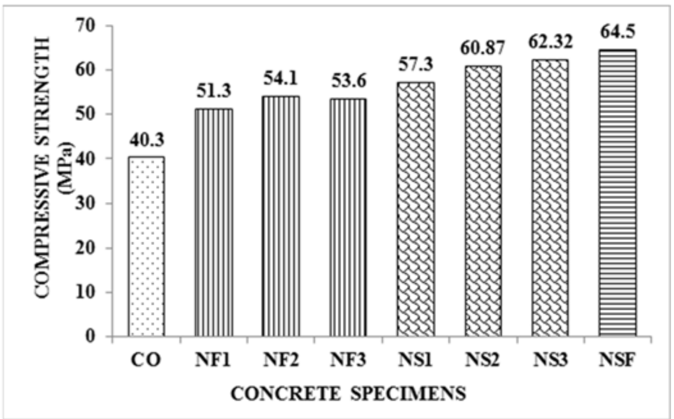

Figure (1): Compressive strength test results of examined specimens

Water Absorption Test

Figure 2 presents the results of water absorption test. It is viewed that increasing the percentage of nanoparticles caused a declining trend in the absorption of water in the concrete specimens. It is clear that NS3 specimen shows a steep reduction in water penetration among all other nanoparticles and this is due to that the size of particles helps seal the gel pores present in the concrete mixture. With a higher content of nano-Fe_2O_3 (NF3) and nano-SiO_2 (NS3), a sharp drop in water absorption is noted of about 54.16% and 35.83%, respectively. The reason is due to densified micro-structure and refined pores. NSF group specimens indicate about 64.17% reduction in water penetration with respect to the control group mixture. This is due to pores becoming filled up with nanoparticles, which results in the reduction of permeable voids present in the examined concrete specimens.

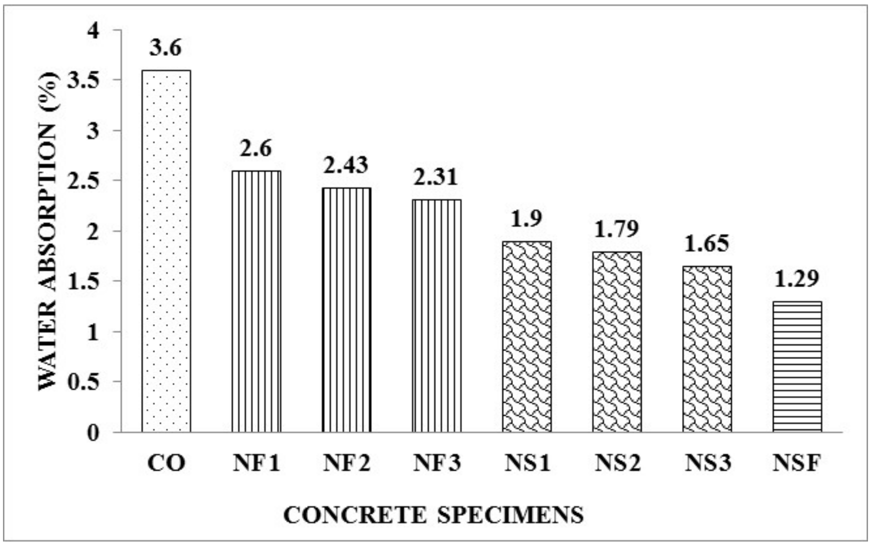

Figure (2): Water absorption test results of examined specimens

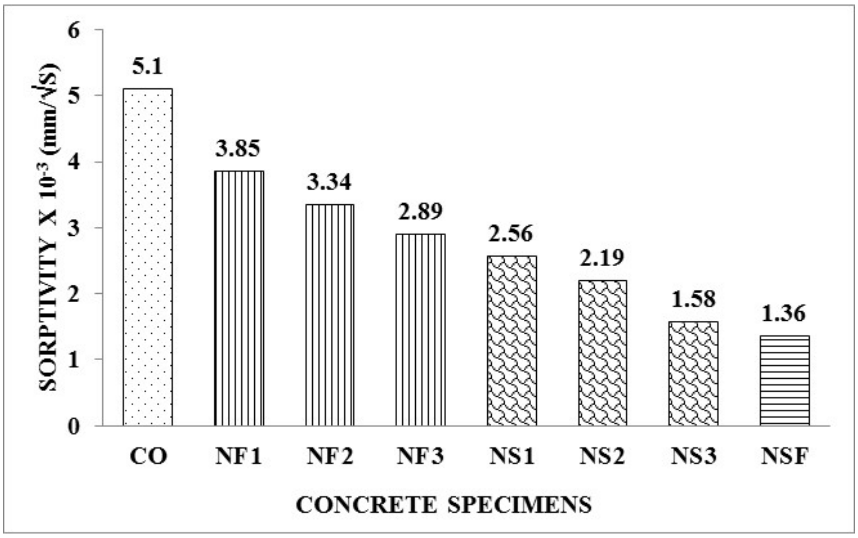

Figure (3): Water sorptivity test results of examined specimens

Water Sorptivity Test

Sorptivity coefficients of concrete specimens are measured and plotted in Figure 3. As expected, sorptivity is appreciably reduced in nanoparticle-added concrete. The sorptivity coefficient decreased by 43.33% and 69.01% corresponding to 1.5% addition of nano-Fe_2O_3 (NF3) and nano-SiO_2 (NS3) with reference to the control group. But, in the case of NSF group specimen, the sorptivity coefficient is 73.33%, which is lower than that of CO group. This is attributed to that the inclusion of nanoparticles filled the pores between the binder paste and aggregate interface, thus reducing the action of capillary pores. The reason for such trend in the sorptivity values is also due to modification of micro-structure in the existence of nanoparticles, wherein these nanoparticles hold together to form a gel chain by acting as kernels. The discrete and continuous voids present in specimens are filled up with the nanoparticles, thus reducing the capillary suction of water into the specimens.

Table 3. Charge passed and chloride ion penetrability (ASTM C1202)

Charge passed (Coulombs)	Chloride ion penetrability
> 4000	High
2000 – 4000	Moderate
1000 – 2000	Low
100 -1000	Very low
< 100	Negligible

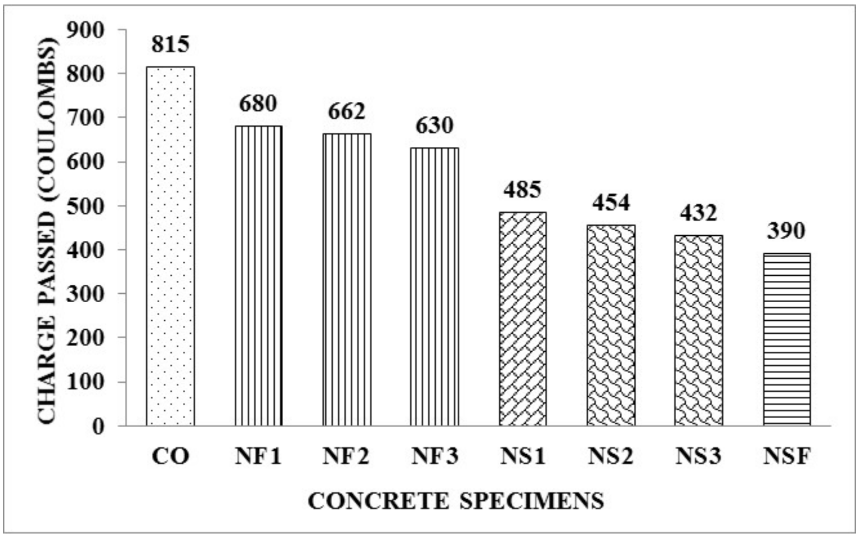

Figure (4): Chloride ion penetrability results of examined specimens

Chloride Ion Penetrability Test

The standard (ASTM C1202) prescribed the criteria for correlating the charge passed (Coulombs) and the chloride ion penetrability as indicated in Table 3. Figure 4 depicts the experimental results of charge passed (Coulombs) by chloride penetration test. The addition of nanoparticles in concrete specimens (NS, NF and NSF) shows a positive progressive improvement in terms of resistance to permeation of chloride ions in concrete specimens. The experimental results indicate that chloride permeability of nanoparticle-added concrete mixtures dropped dramatically to a lower level. All the examined specimens are under low chloride ion penetrability as per the standard shown in Table 3. A lower chloride ion charge passage is noticed in NF3 and NS3 specimens of about 35.97% and 56.09%, respectively, compared with that of the control. It is noted that NF3 and NS3 show 35.97% and 56.09% lower charge passage, respectively, compared with that of the control. A considerable reduction in the total charge passed of about 60.37% is observed for NSF group specimen. Thus, combination of nano-SiO_2 and nano-Fe_2O_3 particles provided a pore refining effect, which results in the downgrading of total Coulomb charge passed.

Correlation Evaluation of the Results

The correlation expression is developed between compressive strength and durability indices including water absorption, sorpitivity and chloride ion permeability characteristics as shown in Figures 5 and 6. The value of regression coefficient (R^2) and its corresponding linear equation are presented in Figures 5 and 6. R^2 coefficients of 0.98, 0.96 and 0.93 are greater than 0.85 (Montgomery and Peck, 2015), exhibiting a remarkable correlation between the chosen parameters. The correlation expression can be adopted in designing nano-modified concrete.

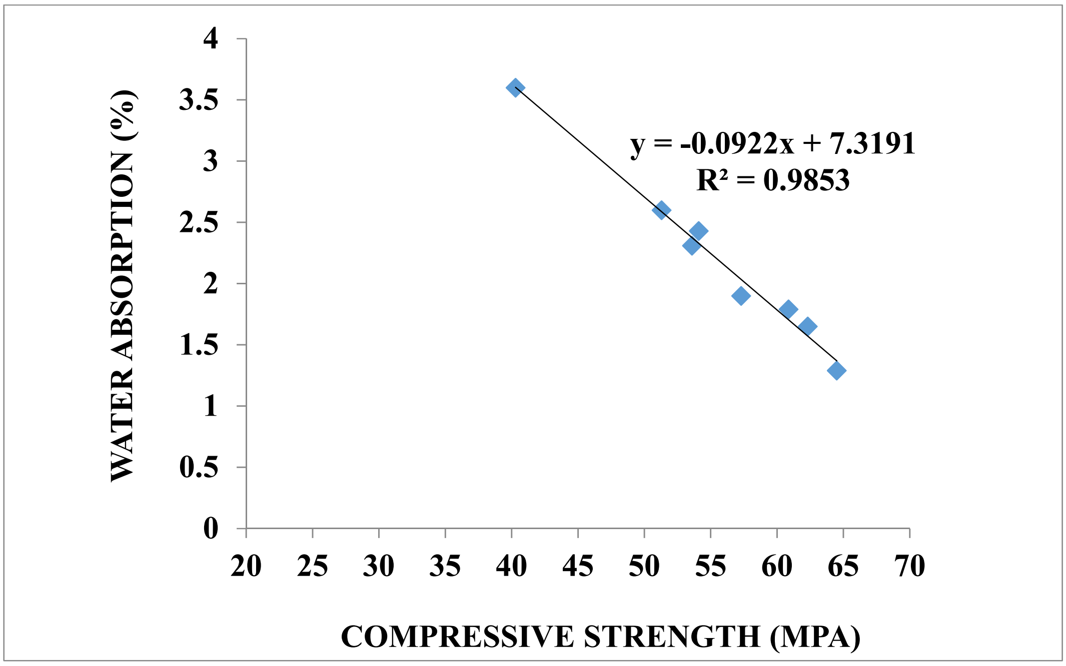

Figure (5): Correlation evaluation between water absorption and compressive strength of concrete

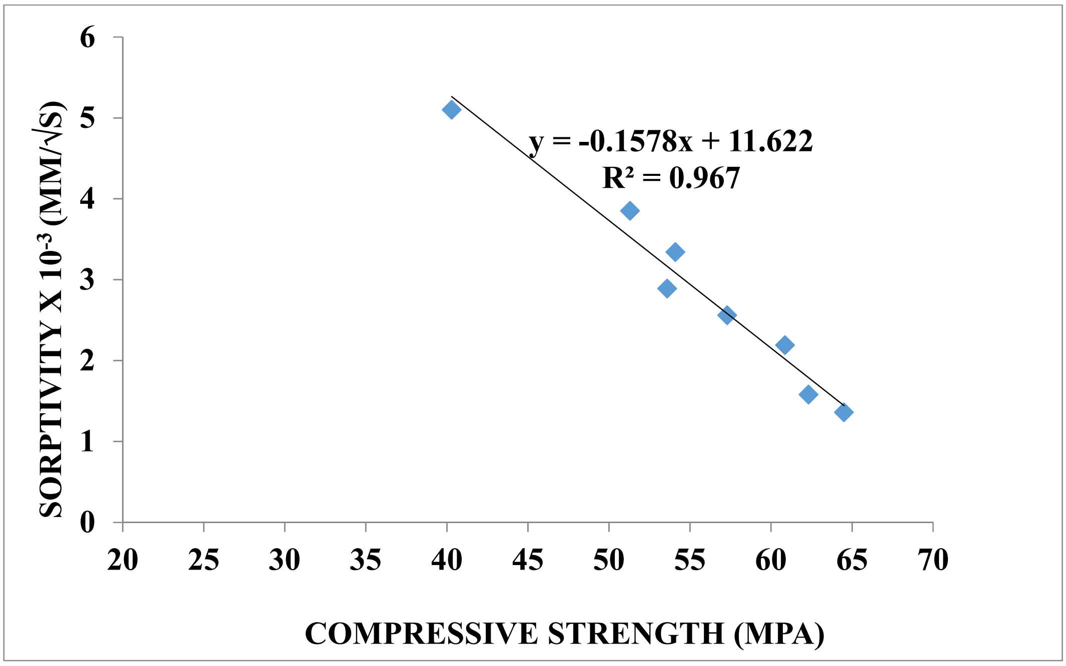

Figure (6): Correlation evaluation between sorpitivity and compressive strength of concrete

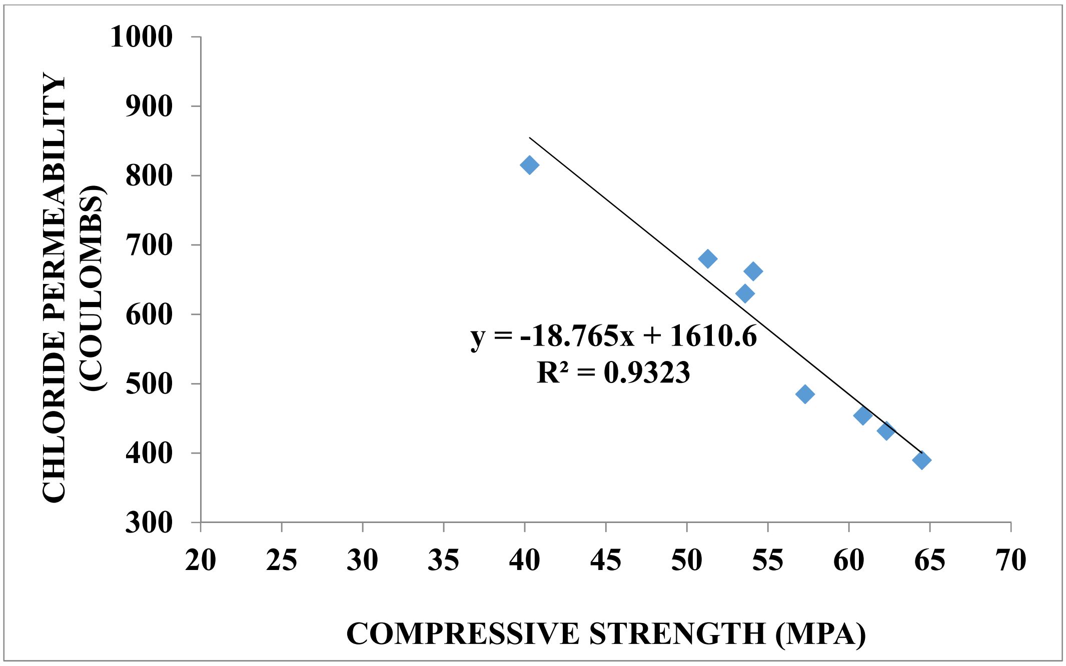

Figure (7): Correlation evaluation between chloride permeability and compressive strength of concrete

CONCLUSIONS

From this study, the following conclusions can be drawn:

1. With the addition of nanoparticles in concrete, the fluidity of the mixture reduced with reference to control which is due to high fineness of nanoparticles.
2. Nano-modified concrete performed well in compressive strength test and showed significant enhancement for binary combination (NSF) of nanoparticles. In the NS group specimens, addition of 1.5% of nano-silica (NS3) showed a more significant effect than those of the control and NF group specimens.
3. With respect to compressive strength characteristics, on adding single nanoparticles (among NS and NF groups), 1.5% of nano-silica and 1% of nano-ferric oxide is found to be the optimum dosage for the preparation of concrete.
4. NS series concrete mixture performed better in terms of permeability resistance in water absorption by immersion than the NF series mixture.
5. The concrete containing 0.5% each of nano-silica and nano-ferric oxide particles (NSF) greatly reduced the sorptivity coefficient.
6. In nanoparticle-added concrete samples, chloride permeability rate is dramatically decreased.
7. The incorporation of nanoparticles in concrete helps prevent steel corrosion embedded in concrete.
8. A linear correlation is well established between compressive strength and durability indices including water absorption, sorpitivity and chloride ion permeability characteristics.

REFERENCES

Berryman, C., Zhu, J., Jensen, W., and Tadros, M. (2005). “High-percentage replacement of cement with fly ash for reinforced concrete pipe”. Cement and Concrete Research, 35 (6), 1088-1091.

Camcho, R.E.R., and Afif, R. U. (2002). “Importance of using the natural pozzolans on concrete durability”. Cement and Concrete Research, 32, 1851-1858.

Choolaei, M., Rashidi, A.M., Ardjmand, M., Yadegari, A., and Soltanian, H. (2012). “The effect of nanosilica on the physical properties of oil well cement”. Materials Science and Engineering, 538, 288-294.

Dinakar, P., Pradosh, K., Sahoo, and Sriram, G. (2013). “Effect of metakaolin content on the properties of high-strength concrete”. International Journal of Concrete Structures and Materials, 7, 215-223.

Gjorv, O. E. (2011). “Durability of concrete structures”. Arabian Journal of Science and Engineering, 36, 151-172.

Jo, B.W., Kim, C.H., and Lim, J.H. (2007). “Investigations on the development of powder concrete with nano-SiO_2 particles”. KSCE Journal of Civil Engineering, 11, 37-42.

Liu, X., Chen, L., Liu, A., and Wang, X. (2012). “Effect of nano-$CaCO_3$ on properties of cement paste”. Energy Procedia, 16, 991-996.

Mohseni, E., Miyandehi, B.M., Yang, J., and Yazdi, A. (2015). “Single and combined effects of nano-SiO_2, nano-Al_2O_3 and nano-TiO_2 on the mechanical, rheological and durability properties of self-compacting mortar containing fly ash”. Construction and Building Materials, 84, 331-340.

Montgomery, D. C., and Peck, E. A. (2015). “Introduction to linear regression analysis”. 5th Edn., Wiley, New York.

Nazari, A., and Shadi, R. (2011). “The effects of ZnO_2 nanoparticles on strength assessments and water permeability of concrete in different curing media”. Materials Research, 14 (2), 178-188.

Nazari, A., Shadi, R., Shirin, R., Shamekhi, S.F., and Khademno, A. (2010). "Mechanical properties of cement mortar with Al_2O_3 nanoparticles". Journal of American Science, 5 (7), 94-97.

Oltulu, M., and Sahin, R. (2011). "Single and combined effects of nano-SiO_2, nano-Al_2O_3 and nano-Fe_2O_3 powders on compressive strength and capillary permeability of cement mortar containing silica fume". Materials Science and Engineering (A), 528, 7012-7019.

Qing, Y., Zenan, Z., Deyu, K., and Rongshen, C. (2007). "Influence of nano-SiO_2 addition on properties of hardened cement paste as compared with silica fume". Construction and Building Materials, 21, 539–545.

Sanchez, F., and Sobolev, K. (2010). "Nanotechnology in concrete – a review". Construction and Building Materials, 24, 2060-2071.

Scrivener, K. L., and Kirkpatrick, R. J. (2008). "Innovation in use and research of cementitious materials". Cement and Concrete Research, 38 (2), 128-136.

Senff, L., Labrincha, J.A., Ferreira, V.M., Hotza, D., and Repette, W.L. (2009). "Effect of nano-silica on rheology and fresh properties of cement pastes and mortars". Construction and Building Materials, 23, 2487-2491.

Senff, L., Tobaldi, D.M., Lucas, S., Hotza, D., Ferreira, V.M., and Labrincha, J.A. (2013). "Formulation of mortars with nano-SiO_2 and nano-TiO_2 for degradation of pollutants in buildings". Composites (B), 44, 40–47.

Seshasayi, L.V.A., Ramaseshu, D., Svnopsis, and Shankaraiah, R. (2001). "Effect of cement replacements by fly ash and silica fume on compressive strength of concrete". American Concrete Institute, Special Publication, 199, 581-594.

Siddique, R., and Kaur, D. (2012). "Properties of concrete containing ground granulated blast furnace slag at elevated temperatures". Journal of Advanced Research, 3, 45-51.

Sobolev, K., Flores, I., Hermosillo, R., and Martinez, L.M.T. (2008). "Nanomaterials and nanotechnology for high-performance cement composites". American Concrete Institute, Special Publication, 254, 93-120.