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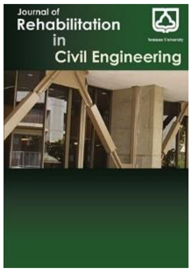

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Evaluation of Mechanical Properties and Durability of Concrete Pavement Containing Electric Arc Furnace Slag and Carbon Nanostructures

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ABSTRACT

The destructive effects of global warming have attracted attention to the optimal using of resources and recycling. Therefore, slag has been considered as a solution in various industrial sectors including the road construction. Also, among the new materials, cement carbon nanostructures which can improve the concrete mechanical properties and resistance are used. These nanostructures are produced through Chemical Vapor Deposition method during the cement production process on the type II cement. In this study, it is aimed to improve the mechanical properties and resistance of concrete pavements with slag and cement carbon nanostructures. The results showed that using 66% slag and 5% cement carbon nanostructures (SC66N5) have been shown the best performance in concrete pavements. Increasing the amount of slag and carbon nanostructures enhance the compressive strength, flexural strength, tensile strength, chlorine passing current and durability against freezing and thawing cycles, and decrease permeability and water absorption percentage. The results showed that in SC66N5 28-day sample, the compressive strength (52%), flexural strength (32%), tensile strength (53%), chlorine passing current (88%) and passing ultrasonic pulse velocity after freezing and thawing (7%) are increased with respect to the cement concrete sample. Furthermore, the permeability (46%), water absorption percentage (45%), weight loss after freezing and thawing cycles (78%) are reduced in comparison to the cement concrete sample. The results revealed that using slag and cement carbon nanostructures improve the durability of concrete pavements.

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1. Introduction

The ever-increasing development of the steel industry as a critical industry during recent decades has led to the extensive production of side products, especially the steel slag. As there is no defined and determined usage for these products, they are stored in the form of big depots in the factory campuses. Sustainable development based on considering environmental protection and conservation have forced countries all over the world to seek an approach to modify the usage of such valuable resources[1], [2]. Steel slag can be used as the ideal rock material in road construction. On the other hand, using slag prevents from extracting thousands of tons of natural rock materials from mines and river beds[3]. Also one of the central aspects of nanotechnology is its interdisciplinary nature, interaction between this science and concrete science may be a turning point in the road construction industry. The ultimate goal in investigating concrete at nano-scale is to introduce a new generation of materials with high performance and create new and different properties rather than properties of ordinary materials[4]. Nanomaterials incorporating in concrete increased its resistance and durability. To study concrete, the particles size has to be at least 500 nm. Also, the additives used in the pavement don't always improve concrete properties. Nanotechnology has shown its comprehensive capability indefinitely enhancement performance. Nanoparticles fill the specific voids according to their sizes and also promote concrete features by producing nano-crystals. Cement carbon nanostructures are known as one type of nanoparticles which strengthen and improvement the mechanical and physical characteristics of concrete. Furthermore, investigation of the improvement effects of these materials in different technical fields requires more comprehensive studies[5], [6].

For example, Patel et al., examined the application of slag in concrete and found that by increasing the proportion of slag grains from 40% to 65%, the compressive strength is increased from 31.4 MPa to 42.7 MPa. Using a mixture with accurate grading improveing the mechanical characteristics and durability of slag-contained concrete compared with ordinary concrete[7]. Lam et al. studied the resistance and sustainability of roller-compacted concrete with electric arc furnace slag aggregate and fly ash. They resulted that by increasing the slag ratio, the compressive strength and sulfate strength are decreased somehow, but the abrasion resistance and percentage of water absorption are increased[8]. Pomaro et al. assessed the concrete containing blast slag. They concluded that both types of residues have a positive effect on the features of soft cement and mechanical characteristics of hard concrete[9]. Penteado et al. used electric arc furnace slag as natural aggregate in concrete block pavements. The results showed that by increasing the percentage of used slag, the compressive strength increased, but the percentage of water absorption decreased somehow. By addition of 75% slag, the 7-day compressive strength increased by 13.5% with respect to 56-day compressive strength, and due to the technical and environmental requirements, this study has recommended the use of electric arc furnace slag in concrete[10]. Yeih and Chang have investigated the effects of four types of cement (type I cement, type II cement, sulfur aluminate cement ,and calcium aluminate cement) and two curing types (water curing and air curing) on the properties of prefabricated concrete made up of electric arc furnace slag as aggregate. They found that by increasing the amount of type II cement, the compressive strength and concrete abrasion increased, and the compressive strength of concrete with type II cement was higher than that of type I cement. The concrete with sulfur aluminate cement reduces the compressive strength and flexural strength especially in the water curing type[11]. Nadeem et al. The mechanical properties of slag-containing concrete were investigated, and found that using more than 100% slag as aggregate, significantly increases the concrete mechanical properties and its abrasion resistance by 50%, in comparison with the ordinary concrete[12]. Tarawneh et al. used steel slag as a substitute in the concrete mixture. The slag aggregate containing concrete exhibits higher abrasion resistance, and impact factor rather than the ordinary aggregates containing concrete. Also, the compressive strength is higher for the 7- day sample with respect to that of the 28 day sample. It has been observed that the effect of coarse aggregates on the compressive strength is significant due to their high weight and mass [13]. The initial studies regarding the freezing mechanism and its effect on the concrete were conducted by Powers et al. They maintained that the hardened cement paste and aggregate show different behavior when exposed to the freezing and thawing cycles. Powers has mentioned in his studies from 1945 to 1956 that freezing causes stresses in the cement pores which, due to the hydraulic pressure, could damage concrete[14]. Jiang et al. investigated the effect of sulfates in the vicinity of concrete structures. They found that sulfate mixtures have both positive and negative effects on the concrete exposed to freezing and thawing. The positive impact of such solutions is reduction of the freezing temperature and decrease of sulfate attacks during the freezing and thawing cycles. The negative effect is due to the expansive products which cause micro-cracks in concrete and accelerate concrete damage[15]. Yingfang et al. studied the impact of nano-kaolinite on concretes exposed to freezing and thawing cycles. Numerous tests have been performed to determine the concrete durability against concrete freezing and thawing cycles for samples containing 1%, 3%, and 5% nano-kaolinite. It was known that by increasing the number of freezing and thawing cycles, the weight loss occurs gradually in non-kaolinite samples and samples with 1% and 5% nano-kaolinite. But in concrete samples with 3% nano-kaolinite there was increase in the weight during the whole period of freezing and thawing cycles. After finishing 125 cycles of freezing and thawing, the highest weight loss was equal to 5.13%, which corresponded to the non-kaolinite sample[16].

Fakhim et al. investigated the effect of carbon nanotubes on cement hydration and quality improvement of such products using different multilayer carbon nanotubes that contained 0.1%, 0.3%, 0.5% ,and 1% cement (the water to cement ratio was constant equal to 0.4). The thermal gravimetric analysis revealed that using 0.3% multilayer carbon nanotubes exhibited the most qualified hydration products[17]. Shah et al. studied that dispersion of 0.02% to 0.33% of multilayer carbon nanotubes within the solution of water and surfactant, by implementation of optimal ultrasonic energy and then added cement contained 0.3 and 0.5 water to cement ratio. They concluded that using 0.03% to 0.1% multilayer carbon nanotubes led to the best mechanical properties of cement nanocomposites, and Young's modulus are increased by 15% to 55%. In addition, flexural strength increases by 8% to 48% but condensation decreases by 30% to 40%[18]. Hakamy et al, investigated nano clay, and nanocarbon at 1%, 2%, and 3% concentrations in concretes. The results showed that 1% nano clay and 1% nanocarbon increased the density, compressive strength, flexural strength, toughness, impact factor, and hardness concerning the other mixtures[19]. Sun et al. used chemical vapor deposition method to grow directly carbon nanotubes on cement and silica fume. They also used ironstone, and other industrial side products such as the convertor dust and red rose as other catalysts. Their study shows that the final product has high purity. The results of the thermal gravimetric analysis showed that there were 4 % carbon nanotubes in the cement. Based on the obtained results of this study, carbon

Nanotubes' growth on cement through chemical vapor deposition is influenced by some factors such as the substrate, carbon source, temperature, and catalyst, which leads to the production of different products[20].

Rocha et al. investigated the effect of carbon nanotubes on the breaking behavior, flexural strength, and tensile strength of concrete. They made an improved cement paste system with enhanced mechanical properties by adding 0.05% and 0.10% of carbon nanotubes. The presence of 0.1% carbon nanotubes in the cement paste led to a 90% improvement in the breaking energy, 46% in the flexural strength, and 47% in the tensile strength[21]. Dalla et al, investigated the effect of carbon nanotubes on chlorine permeation in cement paste. They found that by increasing the weight percentage of carbon nanotubes, the penetration of chlorine is reduced, but the flexural and compressive strengths are increased[22]. Sikora et al. investigated the effect of carbon nanotubes on the mechanical and microstructural properties of cement paste, including multilayer carbon nanotubes and multilayer carbon nanotubes with nano silica shell, which was exposed to high temperature. The cement paste was filled with three different amounts of nanomaterials at 0.125, 0.25, and 0.5 wt. %. Using 0.125 wt. % of multilayer carbon nanotubes with solid nano-silica shell was more useful in comparison to other combinations of multilayer carbon nanotubes[23]. Kim et al. investigated the dispersion of single-walled carbon nanotubes using an air entraining agent and its application in Portland cement paste. In according to the obtained results, with the addition of single-walled carbon nanotube solutions, the compressive strength, flexural strength and yield stress of cement paste are increased[24]. This research aim is not only improvement the environment but also the effect of slag and cementitious carbon nanotubes on the mechanical properties and durability of concrete are investigated.

2. Experimental program and Materials

2.1. Aggregates

Grading used for making specimens has been displayed in Table 1 and is according to ASTM C33 standard.

Table 1. The analysis of Sieve aggregates.

Coarse aggregates	**Aggregate size(mm)**	25	19	9.5	4.75	2.36
	Percentage of screening sieve (%)	100	96	38	8	0
Fine aggregates	**Aggregate size(mm)**	1.18	0.6	0.3	0.15	0.075
	Percentage of screening sieve (%)	82	58	26	7	2

2.2. Electric arc furnace slag

The slag employed in this study is from Mobarakeh steel Company electric arc furnace slag. This is a combined non-metal slag that contains different percentages of iron oxides, aluminum, manganese, magnesium, and other elements. The slag particles were soaked at least for 24 hours and then the increase in volume test was conducted on them. When the volume increase is less than 0.5%, the test is implemented.

2.3. Water

Urban drinking water without any additives was used in this study.

2.4. Super-plasticizer additives

SPC-N1 Poly-carboxylate ether-based super-plasticizer has been used in this study. The super-plasticizer was incorporated to improve the concrete performance of The specific weight of this substance was 1.1 g/cm^3 at 25 °C.

2.5. Cement

Type II cement was used in this study. The chemical, physical, and mechanical characteristics of this cement are compatible with ASTM C150 Portland cement[25]. Table 2 shows the chemical components of this cement. Brunauer-Emmett Teller test was used to compare this type of cement with the cement containing carbon nanostructures, and Le Chatelier Flask was used to determine the specific surface area and density. Based on Le Chatelier Flask test, the density of cement was equal to 3.17 gr/cm^3. Brunauer-Emmett Teller test yielded 0.998 m^2 as the cement specific surface area.

2.6. Cement carbon nanostructures

In this study, the used cement carbon nanostructures have been grown outright using the chemical vapor deposition during cement production on type II Portland cement. Le Chatelier Flask test showed that the density of cement with carbon nanostructures was 3.03 gr/cm^3. Also, the specific surface area was equal to 2.705 m^2/gr. As the nanostructures used in this study were grown by the chemical vapor deposition method on cement, they were in the form of nanotubes and nanofibers with 20 to 120 nm diameter. The nanostructures length was also variable and reached up to several micrometers and they were present in the base cement from the beginning in the distributed form. Comparing the average cement density (3.17 gr/cm^3) with cement containing carbon nanostructures (3.03 gr/cm^3), it was found that the frequency of carbon nanostructures containing cement was 0.14 gr/cm^3. This reduction could be attributed to a lower density of the main element in the carbon nanostructures, i.e. carbon, concerning that of other constituent elements of cement like iron, aluminum, etc. In this Study, use was made of 2%, 5%, and 10% cement carbon nanostructures as substitutes for the cement. Therefore, the number of incorporated carbon nanostructures for the mentioned percentages was 0.094, 0.235, and 0.471, respectively. Table 2 shows the chemical characteristics of cement carbon nanostructures and Portland cement.

Table 2. The chemical characteristics of cement carbon nanostructures and Portland cement utilizing XRF test.

Percentage of chemical compounds	**Type II Portland cement**	**Cement carbon nanostructures**
Na_2O	0.185	0.274
MgO	2.898	2.867
Al_2O_3	2.995	3.522
SiO_2	21.854	22.293
P_2O_5	0.049	0.126
SO_3	3.816	1.995
K_2O	0.976	0.85
Cao	63.827	63.723
TiO_2	0.331	0.296
MnO	0.224	0.299
Fe_3O_3	2.997	2.849
Sr	0.088	0.065

2.7. Mix design

Volume mix design According to ACI211-89 Standard has been used to make the samples[26]. In the current study, coarse aggregate slag with 0%, 33.3%, 66.6%, and 100% ratio and cement carbon nanostructures with 2%, 5%, and 10% (by weight) replaced the Portland cement. The selection of percentages of cement carbon nanostructures is based on our previous research. [27]. The prepared mixture was placed in a mold at two layers. Then and the sample was compacted 25 times and vibrated. Curing was performed at two-time intervals of 7 and 28 days within the limewater. The implemented mix design of concrete is shown in Table 3 and the experimental program is shown in Table 4. The construction of concrete samples in the laboratory is shown in Fig. 1 shows. The curing of concrete samples in water is shown in Fig. 2.

Fig. 1. The concrete preparation samples in the laboratory.

Fig. 2. The curing of concrete samples in water.

Table 3. Mix design for cement concrete **(**Kg/m^3**).**

Mix design	**Fine aggregates**	**Silica coarse aggregates**	**Cement**	**Cement carbon nanostructures**	**Slag**	**Water**
OPC	1152	768	400	0	0	180
SC33	1152	515	400	0	253	180
SC 66	1152	261	400	0	507	180
SC 100	1152	0	400	0	768	180
SC33N2	1152	515	392	8	253	180
SC33N5	1152	515	380	20	253	180
SC33N10	1152	515	360	40	253	180
SC66N2	1152	261	392	8	507	180
SC66N5	1152	261	380	20	507	180
SC66N10	1152	261	360	40	507	180
SC100N2	1152	0	392	8	768	180
SC100N5	1152	0	380	20	768	180
SC100N10	1152	0	360	40	768	180

Table 4. The experimental program and sample characteristics.

Test	Sample dimensions (mm)	Age (day)	Number of samples in the mix
Compressive strength	150 × 300 Cylinder	7,28	6
Flexural strength	500 × 100×100	7,28	6
Tensile strength	150 × 300 Cylinder	28	3
Permeability of chlorine ion	100 × 50 Cylinder	28	3
Depth of water permeability	200 × 200×120	28	3
Water absorption percentage	100 × 100×100	28	3
Freezing and thawing cycles	370 × 78×78	14,19,23,28,32, 37,41,46,50,54	3

3. Testing methods, results, and discussion

The purpose of the present study is to investigate the effect of slag and cement carbon nanostructures on the mechanical and durability characteristics of concrete.

3.1. Compressive strength

To examine the effect of slag and cement carbon nanostructures on the concrete pavement, six replicas were made from each concrete sample. During the test, and after 7 and 28 days of curing, the cylindrical samples were tested according to ASTM C39 Standard under the jaws of the apparatus to measure their compressive strength[28]. Fig. 3 shows the compressive strength of the samples. Based on the results shown in Fig. 4 the diagram of SC66N5 has the highest compressive strength. This sample could sustain higher stress concerning the other examples, and Ordinary Portland Cement (OPC) has the lowest compressive strength. Increasing the amounts of replaced carbon nanostructures and slag leads to increased compressive strength. By increasing the amount of slag and carbon nanostructures, crystallization occurs more rapidly, and carbon nanostructures fill aggregate pores and voids as complementary fine aggregates in the mixture, which forms a homogenous and dense concrete. This led to reduce the pores and increase the compressive strength due to the better cohesion between the aggregates and the mortar. It is noteworthy that the optimal percentages for the slag and carbon nanostructures are approximately equal to 66% and 5%, respectively. Then the compressive strength is reduced. This behavior is explained in this way that extra amounts of cement carbon nanostructures cause nano agglomeration around cement particles, which causes incomplete hydration of cement particles and generation of hydrated products along with weak bonds. Also using too much slag increases the amounts of voids which leads to An increased amount of water absorbed by the aggregates, which in turn reduces the amount of water in the concrete compound. Therefore, hydration doesn't occur completely and the ultimate strength is reduced[29].

In a 2021, Mohammadi Janaki et al. studied if 5% of carbon nanotubes were used, the compressive strength increased by 15% compared to the conventional concrete sample[27].

Fig. 3. The compressive strength test of samples.

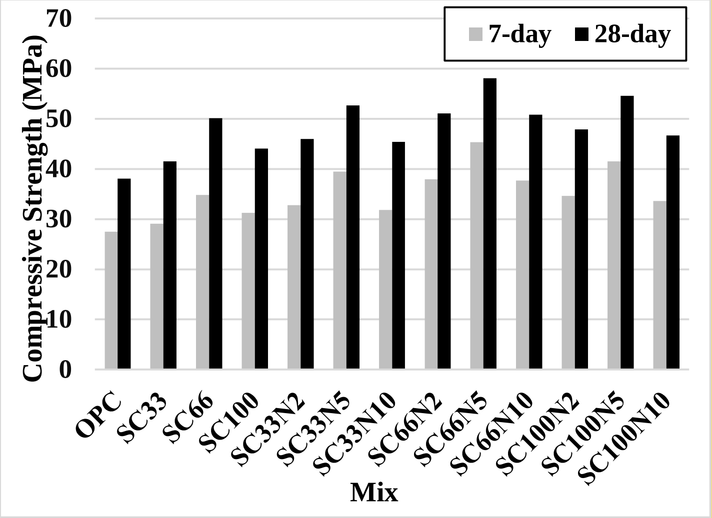

Fig. 4. Compressive strength of samples.

3.2. Flexural strength

In the design of the concrete pavements, to consider the fatigue criterion which controls concrete cracking under cyclic loadings, the flexural strength is used. Flexibility is generated in concrete pavements under axial loads from both the compressive and flexural stresses, although the ratio of compressive stresses to the compressive strength is too small that it does not affect the concrete slab thickness. Hence, the samples were prepared with dimensions of 500×100×100 mm for the flexural strength test to perform this test by ASTM C78 Standard. The samples were placed under the universal testing machine (UTM) After 7 and 28 days of curing with water to measure their flexural strength[30]. Fig. 5 shows the flexural strength test.

As a result, as shown in Fig. 6, the SC66N5 sample has the highest flexural strength, and OPC has the lowest flexural strength. SC66N5 28-day sample has 32% higher flexural strength for the OPC sample. Increasing the amounts of replaced carbon nanostructures and slag lead to increased flexural strength. Therefore the section's flexural strength has increased due to the above-mentioned reasons until reaching an optimal value and then it is reduced due to reduction in strength level against stresses due to applied bending. By increasing the amount of slag and carbon nanostructures, crystallization occurs more rapidly. As well as, carbon nanostructures fill the aggregate pores and voids as the complementary fine aggregates in the mixture, which form a homogenous and dense concrete[29]. This reduces the number of pores and increases flexural strength due to the better bondage between the aggregates and mortar and also reliance of aggregates upon each other. It is noted that the optimal percentages of slag and carbon nanostructures are around 66% and 5% for the slag and carbon nanostructures, respectively. This behavior is described in this way that too much utilization of cement carbon nanostructures leads to nano agglomeration around cement particles, which causes incomplete hydration of cement particles and generation of hydrated products with weak bonds. Also, extra utilization of slag increases the number of voids, and as a result, aggregates absorb more water which reduces the required water in the concrete compound. Therefore, hydration doesn't occur completely and the ultimate strength is reduced.

In a study by Konsta-Gdoutos et al., The flexural strength of concrete increased with increasing percentage of carbon nanostructures. The control of matrix cracks at the nanoscale was also improved[31].

Fig. 5. The flexural strength test.

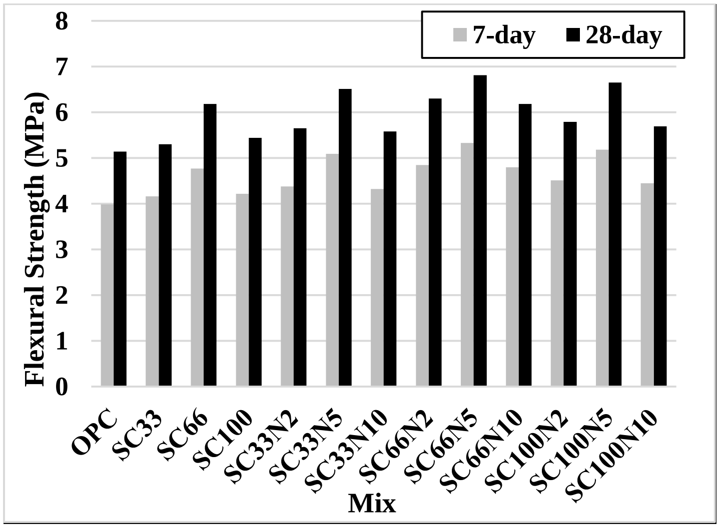

Fig. 6. Comparing the flexural strength of samples.

3.3. Tensile strength

Tensile strength performed on the 28-day cured samples was according to ASTM C496 Standard. During this test, the diagonal compression force was applied on the cylindrical concrete sample (with 15 cm diameter and 30 cm height) which was placed horizontally between the two surfaces of the testing apparatus, and the load was applied continuously without any sudden change and with constant speed around 700 kPa/min to 1400 kPa/min until the concrete ruptures[32]. In according to the results obtained from the above-mentioned studies, the compressive strength of slag-containing concrete has increased concerning the control concrete sample. On the other hand, the tensile strength of the section has increased slightly due to reduced concrete brittleness due to using porous slag aggregates. It is found in Fig. 7 that, increasing the amounts of carbon nanostructures and slag leads to increase of tensile strength. It should be noted that the optimal percentages are around 66% for slag and 5% for carbon nanostructures. Then the compressive strength is reduced. This behavior is explained in this manner that increase of cement carbon nanostructures lead to nano agglomeration around cement particles, which cause incomplete hydration of cement particles and generation of hydrated products with weak bonds. Therefore, the section tensile strength is increased due to the mentioned above reasons until to reach an optimal value. Then the tensile strength is reduced. The SC66N5 sample has the highest tensile strength (5.98 MPa), and this sample can sustain higher stresses due to the applied loading in comparison to the other samples, and sample OPC has the lowest tensile strength (3.91 MPa). Sample SC66N5 exhibits a tensile strength that is 53% higher than that of the OPC sample.

In a study conducted in 2021 by Mohammadi Janki et al. on alkali-activated concrete containing carbon nanotubes, it was concluded that the tensile strength increased with the increase of slag in alkali-activated concrete. And if 5% carbon nanotubes were used, the tensile strength increased by 15% [27].

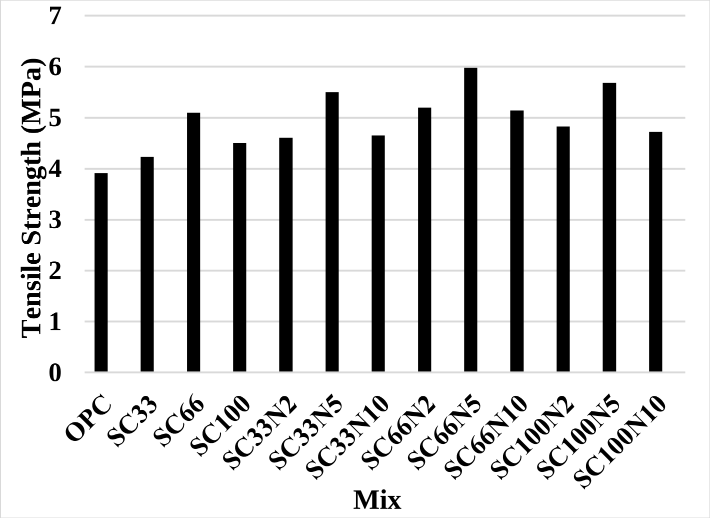

Fig. 7. The results of Tensile strength test of samples.

3.4. Chloride ion permeability

Rapid Chloride Penetration Test (RCPT) was incorporated to measure the concrete resistance against chloride permeation, according to ASTM-C1202 Standard. After placing the concrete in molds, they were covered with wet sheets for 24 hours. Next, the remained samples were soaked inside the saturated limewater to prevent outward leakage of Ca_2OH during curing. This test was performed on a 28-day cured sample. In this method, the total amount of electric charge flowing through the saturated concrete samples (with 10 cm diameter and 5 cm thickness, and under a constant flow), was measured by applying 63V potential difference through the samples, and after 6 hours the total amount of electric charge flow was measured. The concrete samples had contact with NaCl solution on the one face and with NaOH solution on the other face. The electric charge flows through the samples by applying the potential difference, and chloride ions penetrate the concrete. It is assumed that the electric charge flow through the samples occurs via porous solution which acts as an electrolyte. The connection between pores and the number of pores in the samples greatly affect the electric charge flow and the samples with low porosity and pores connection exhibit a lower flow than other samples. This method measures the flow of electric charge through the concrete sample which is known as the chloride permeability index[33].

The results of RCPT given in Fig. 8 show that the SC66N5 sample (5950 Coulombs) has the highest passing flow, and sample OPC (3148 Coulombs) has the lowest passing flow. The amount of electric charge flowing through the SC66N5 sample is increased by 88% with respect to the OPC sample. The results demonstrated a considerable reduction of chloride permeability into the SC66N5 example, which causes an increase in the electric charge flow. Finally, it is concluded that an increase in the replaced carbon nanostructures and leads to an increase in the electric charge flow. It is essential to note that this increase has an optimal value of around 66% for slag and 5% for carbon nanostructures, and then the flow is reduced. By increasing the amounts of slag and carbon nanostructures, crystallization occurs more rapidly and also carbon nanostructures fill aggregate pores and voids as complementary fine aggregates in the mixture, which forms a homogenous and dense concrete. This reduces the pores and increases the electric charge flow through the concrete.

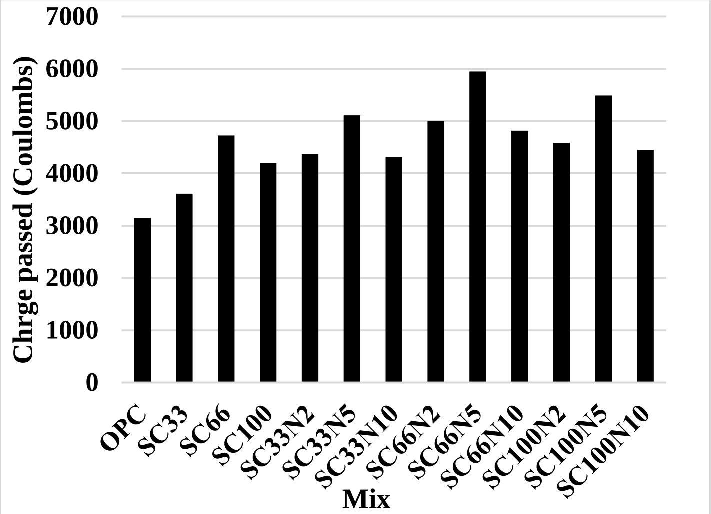

Fig. 8. Electric charge flow through the concrete samples.

3.5. Water permeability

To perform the water permeability test under pressure, to concrete samples with 200×200×120 mm dimensions were made according to EN 12390-8 Standard. After 28 days of curing. The samples were placed in the oven at 100°C temperature and then set at 24±2 temperature to reach the ambient temperature. Then the samples were placed in the permeability test apparatus under 5 bars pressure applied for 72 hours. Then the samples were cut into two pieces and tested by the Brazilian Test Apparatus, and the maximum depth of the water permeability was measured [34]. Fig. 7 shows the depth of water penetration test.

As shown in Fig. 9, the changes in permeability concerning the slag and carbon nanostructures percentages. Based on the results, the SC66N5 (19 mm) sample has the lowest water permeability depth, and the OPC (35 mm) sample has the highest water permeability depth. The SC66N5 sample exhibits a reduction of 46% in water permeability depth concerning that of the OPC sample. Increasing the amount of replaced carbon nanostructures and slag lead to increase of water permeability depth. The water permeability depth has an optimal value of around 66% for slag and 5% for carbon nanostructures, then the amount of penetrated flow increases. This behavior is explained in this way that by an increase in the amounts of slag and carbon nanostructures, nanoparticles react with hydroxide calcium within the hydrated products. This reaction results to the generation of dense C-S-H gel and the cement paste would have a denser structure. On the other hand, the slag-containing concretes experience less cracking due to their higher strength concerning the ordinary concretes, and their permeability is reduced. But higher than the specified limits, the number of pores is increased due to the increased amounts of slag and carbon nanostructures. Consequently, the aggregates absorb more water which reduces water in the concrete compound and therefore hydration is not completely achieved. Furthermore, nanomaterials agglomerate around cement particles which result to incomplete hydration of cement particles and generation of hydrated products with weak bonds that is increased permeability.

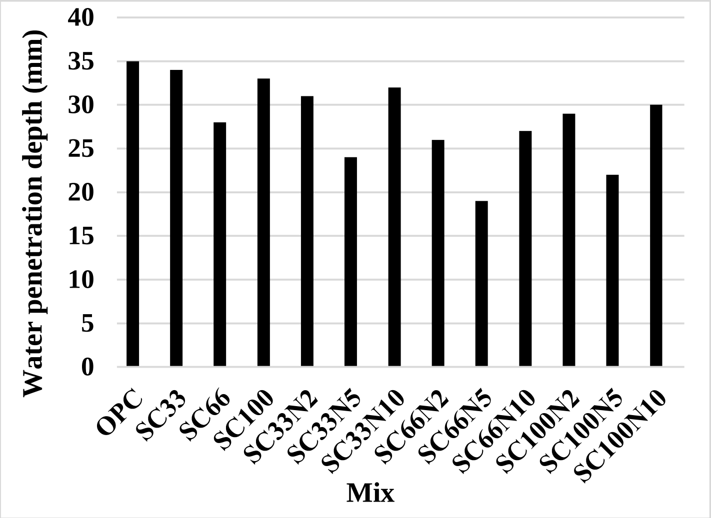

Fig. 9. Water permeability depth in different concrete samples.

3.6. Water absorption percentage

According to ASTM C642, 100 mm^3 cubical samples, after 28 days of curing were placed inside the oven for 72 ±2 hours at 110 ±5 °C temperature. Then the weight of sample (A) was measured accurately. In the next step, the samples were soaked inside water for 24 ±2 hours, and their surface water was dried with a wet sheet (saturated with the dry surface), and the weight was determined (B). Finally, the water absorption percentage was calculated using the volumetric method based on equation 1. Fig. 10 shows the results of the water absorption percentage.

$$AC(\%) = \frac{(B-A)}{A} \times 100 \qquad (1)$$

Based on the Fig. 9, the percentage of water absorption is decreased with an increase of slag and carbon nanostructures amounts. The control concrete sample has the highest water absorption percentage (2.55%), and SC66N5 (1.40%) has the lowest water absorption percentage. It is concluded that by an increasing in the slag and carbon nanostructures percentages, the water absorption percentage is decreased. This reduction in water absorption percentage has an optimal value around 66% for slag and 5% for carbon nanostructures, and then this percentage is increased. In the SC66N5 concrete sample, the amount of water absorption is decreased by 45% concerning that of the OPC sample. However, these samples exhibit lower absorption percentage values than the control sample.

In a study conducted in 2020 by Shafabakhsh and Mohammadi, nano Clay was used with percentages of 1wt%, 2wt% and 3wt% and it was concluded that the best mixing design. It is shown that if 1wt% nano clay was used, the water absorption percentage is decreased by 54%[27].

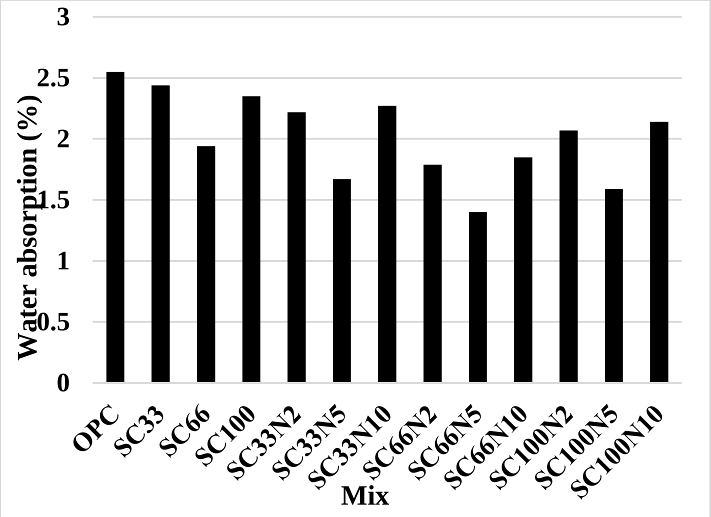

Fig. 10. Water absorption percentage.

3.7. Freezing and thawing cycles

To evaluate concrete durability under freezing, and thawing cycles, ultrasonic, weight loss and flexural strength loss tests were conducted by ASTM C666 Standard. The samples, after 14 days of curing, were soaked inside limewater within the freezing and thawing cycle apparatus. It is noted that samples were placed inside the freezing and thawing apparatus according to method A explained in ASTM C666 Standard. The above-mentioned samples were taken out of the device after enduring 36 cycles, and their weight loss and passing pulse velocity were measured, and then their water was changed. Each freezing and thawing cycle begins at +4.4 °C temperature and decreases until -17.8 °C with a constant rate, and then it is increased up to +4.4 °C to complete a period. This process continues until the samples experience 300 cycles and the flowing pulse velocity and weight loss are measured again at the 300th cycle. Finally, the flexural strength test is conducted on them.

3.7.1. Ultrasonic results

The speed of passing ultrasonic pulse is measured according to ASTM C597 Standard. The Ultrasonic Pulse Velocity (UPV) method including measurement of pulse speed, which is sent by the transmitting transducer from one side of the concrete and received by the receiving transducer at the other side of the concrete[35]. Fig. 11 shows the ultrasonic test, and Table 5 shows the ultrasonic test results for the concrete samples. Based on the findings at the 300th cycle, the SC66N5 sample has the highest pulse velocity, and the OPC sample has the lowest pulse velocity. During the period between 180th to 300th cycles, the samples show a reduction in pulse velocity. An increase in the amounts of replaced carbon nanostructures and slag leads to increased pulse velocity. This increase has an optimal value of around 66% for slag and 5% for carbon nanostructures, then the pulse velocity is decreased. However, these samples have a lower flowing pulse velocity concerning the control sample. By increasing the amount of slag and carbon nanostructures, slag porosity provides concrete with extra space for water volume increase during freezing, which prevents concrete cracking, and provides better cohesion between the aggregates and mortar, and also better aggregates reliance on each other. However, with excessive use of slag and high porosity of slag causes more water absorption, which water absorbed during freezing increases internal stresses and thus reduces the durability of concrete. Also, nanomaterials agglomerate around cement aggregates, which results to incomplete hydration of cement aggregates and generation of hydration products with weak bonds.

Fig. 10. Ultrasonic test apparatus.

Table 5. Pulse Transmission Speed (m/s).

Mix Design	**Number of cycles**									
	0	**36**	**72**	**108**	**144**	**180**	**216**	**252**	**288**	**300**
OPC	4592	4230	3865	3525	3176	2840	2481	2158	1801	1668
SC33	4609	4221	3879	3519	3182	2837	2489	2144	1811	1684
SC66	4815	4415	4036	3674	3319	2960	2598	2238	1891	1755
SC100	4601	4239	3875	3527	3187	2842	2494	2149	1815	1697
SC33N2	4699	4309	3939	3585	3240	2888	2535	2184	1845	1750
SC33N5	4830	4429	4049	3685	3330	2969	2606	2245	1897	1770
SC33N10	4614	4222	3859	3513	3174	2830	2484	2140	1808	1710
SC66N2	4824	4424	4044	3681	3326	2965	2603	2242	1894	1765
SC66N5	2854	4451	4069	3703	3346	2984	2619	2256	1906	1784
SC66N10	4732	4339	3967	3610	3262	2909	2553	2200	1858	1757
SC100N2	4758	4363	3988	3630	3280	2925	2567	2212	1868	1753
SC100N5	4838	4436	4055	3691	3335	2974	2610	2249	1900	1776
SC100N10	4712	4321	3950	3595	3248	2896	2542	2190	1850	1752

3.7.2. Results of flexural strength after freezing and thawing cycles

To investigate the process of flexural strength reduction, several samples were cured inside limewater and other samples were placed in the freezing and thawing apparatus with 300 continuous freezing and thawing cycles. Then the flexural strength test was conducted on them. According to the diagram given in Fig. 12, sample SC66N5 has the highest flexural strength and sample OPC has the lowest flexural strength. Increasing the amounts of replaced carbon nanostructures and slag leads to an increase in flexural strength. This increase has an optimal value of around 66% for slag and 5% for carbon nanostructures, then flexural strength is decreased. However, these samples have lower flexural strength concerning that of the control sample. The flexural strength of sample SC66N5 has decreased by 17.4% concerning the state before applying the freezing and thawing cycles. By providing suitable conditions for concrete paste, there is a higher probability of achieving dense and resistant concrete. Finally, water escape during the freezing process causes an increase in the durability of concrete samples containing slag and carbon nanostructures concerning OPC samples.

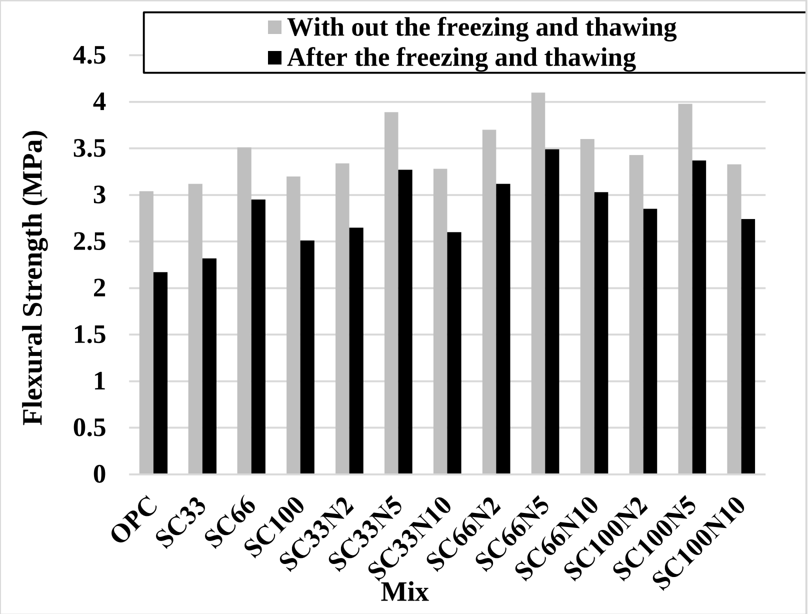

Fig. 12. Comparison between the flexural strengths of different samples by performing freezing and thawing cycles and without the freezing and thawing cycles**.**

3.7.3. Weight loss

According to ASTM C666 Standard, one of the tests by which one could investigate concrete durability against freezing and thawing cycles is comparing weight loss in samples due to the freezing-thawing cycle loading. . The samples are taken out of the apparatus after every 36 cycles and cleaned with a wire brush then they are left to be drained. Next, the samples are weighed by a digital weighing scale and placed again inside the molds and put inside the apparatus to be loaded by the freezing and thawing cycle.

The diagram in Fig. 13 shows the weight loss process in the samples. As it is observed, the sample with 66% slag and 5%

carbon nanostructures have the minimum weight loss, and sample OPC has the least resistance against the freezing and thawing cycle and experiences a higher weight loss. It should be mentioned that at the initial cycles weight change has a higher rhythm and this rhythm is reduced, and from the 180 th cycle on, the trend of weight loss is accelerated. By providing appropriate conditions for concrete paste (concrete paste completes hydration process through absorbing the pores' moisture without making extra pores or cracks due to the evaporation, within the concrete paste). It is possible to achieve a denser concrete with higher strength (Due to the higher strength aggregates). Ultimately, water escapes during freezing (volume increase due to the water freezing inside concrete) into the slag aggregate pores while freezing provides a higher durability for the concrete containing slag and carbon nanostructures. As stated before, slag aggregates have a higher porosity concerning silica aggregates, which increases the number of capillary pores, and consequently increases concrete durability against freezing due to water freezing inside the concrete and increase in the volume. As it is observed, the SC66N mix design has the lowest weight loss and higher durability against the freezing and thawing cycles concerning other samples.

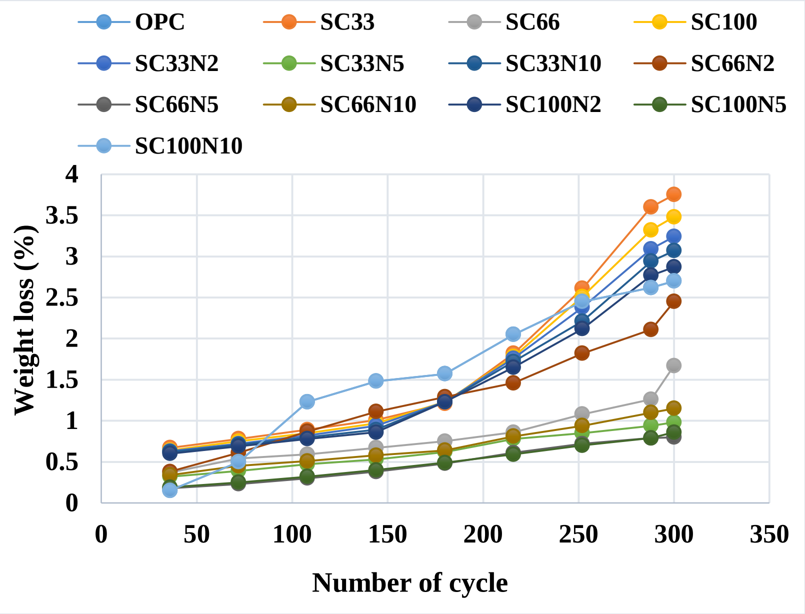

Fig. 13. Weight loss depicted by cumulative percentage**.**

3.8. Relationships

A linear relationship was written between the compressive strength results, and water permeability depth, also between the flexural strength test, and water absorption percentage (Figs. 14 and 15). There is a linear correlation with 0.926 regression coefficient between the compressive strength and water permeability depth as seen in Fig. 14. There is a direct correlation with 0.919 regression coefficient between the flexural strength and water absorption percentage. This linear correlation shows that there is an inversely proportional relationship between compressive strength and water permeability depth as well as between flexural strength and water absorption percentage. It means that, the water permeability and water absorption percentages are decreased by increasing the compressive strength and flexural strength, respectively. Increasing the amounts of slag and carbon nanostructures increases the generation of C-S-H gel due to the pozzolanic activity, which fills concrete pores and reduces concrete permeability and water absorption. It is essential to mention that all the study results correspond to 28-day cured samples.

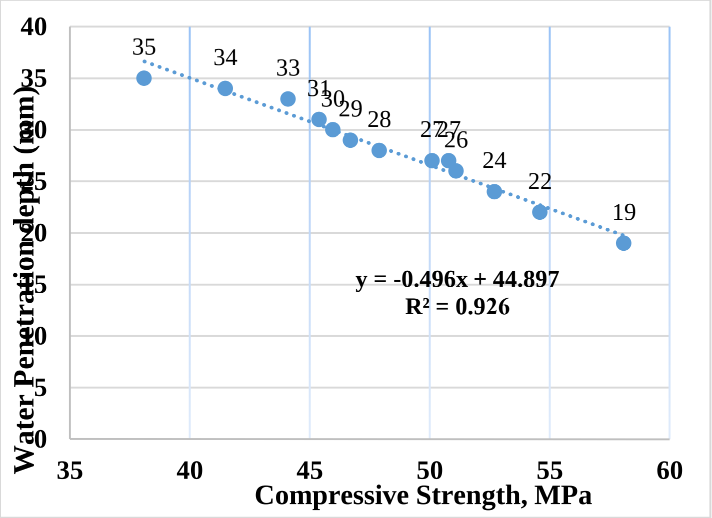

Fig. 14. The relationship between the compressive strength and water permeability depth.

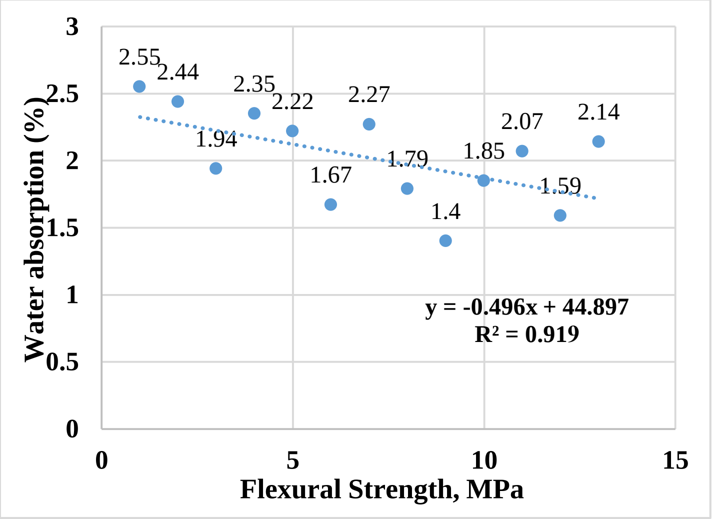

Fig. 15. The relationship between the flexural strength and water absorption percentage.

4. Conclusion

In this study, the effect of slag and carbon nanostructures on concrete pavement are investigated. After the tests are performed and analyzing the samples, the following results are represented as the findings of the current study:

1. Concrete pavements containing slag and carbon nanostructures could be more durable than cement concrete due to their alumina-silica structure. The objective of this experimental study was to investigate some durability parameters of the concrete samples containing slag and carbon nanostructures. The obtained results are as follows:
2. The mechanical properties of concrete pavements and durability of concrete

were increased due to the utilization of slag and cement carbon nanostructures.

3. The compressive strength, flexural strength, tensile strength, chloride passing flow, and resistance against freezing and thawing cycle were increased because of the presence of slag and carbon nanostructures in the concrete. Furthermore, the permeability and water absorption percentage were decreased.
4. It is noted that this increase has an optimal value of around 66% for slag and 5% for carbon nanostructures, and then the concrete mechanical characteristics and durability are decreased.
5. Evaluation of concrete resistance against chloride permeation using RCPT shows that the electric charge flow increases by increasing the amounts of slag and carbon nanostructures.
6. SC66N5 sample has the best mix design under the conditions of 28-day curing, its compressive strength (52%), flexural strength (32%), tensile strength (53%), chloride passing flow (88%) ,and ultrasonic pulse velocity after freezing and thawing cycle 300 (7%) have increased concerning the cement concrete sample. Furthermore, its permeability (46%), and water absorption percentage (45%), weight loss (78%) have decreased in comparison with the cement concrete sample.
7. There is a linear correlation between compressive strength and permeability depth and also between flexural strength and water absorption percentage. This correlation shows an inverse relationship between compressive strength and water permeability depth and even flexural strength and water absorption percentage.

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