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Impact of Graphite Powder on The Properties and Microstructure of Conventional and Silica Fume Concretes

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ABSTRACT

Recently, the production of electrically conductive concrete (ECC) has become widespread by using carbon materials such as graphite powder GP. To eliminate the negative impact of using graphite powder (GP) alone as an additive to concrete, one of the supplementary cementitious materials (SCMs), such as silica fume SF, is combined with graphite powder (GP). In this respect, research work was conducted on concrete mixes with a cement replacement with silica fume with an SF ratio of 10% and with cement replacement levels with graphite powder (GP) ratio of 2.5, 5 and 7.5%. A control concrete mix (MCC) was made with 100% cement with no supplementary cementitious or carbon materials. Concrete mixes were tested in rheological properties such as slump and in hardened properties such as compression, indirect tension and flexural. Concrete samples were tested in compression at the ages of 3, 7, 28 and 90 days and were tested in indirect tension and flexural at the ages of 7 and 28 days. The durability of the concrete samples was examined in both the rapid chloride penetrability (RCP) test and the scanning electron microscopy (SEM) test. The compressive strengths of concrete mixes, MSF-GP2.5, MSF-GP5 and MSF-GP7.5 increase by about 11, -0.3 and -7% compared to MCC but were reduced by about 7, 18 and 21% when compared to MSF, respectively at the age of 28 days. Tensile strengths of concrete mixes, MSF-GP2.5, MSF-GP5 and MSF-GP7.5 were increased by about 19, 3 and -10% compared to MCC but, were reduced by about 7, 20 and 29% compared to MSF, respectively, at the age of 28 days. Flexural strengths of concrete mixes MSF-GP2.5, MSF-GP5 and MSF-GP7.5 increase by about 12, -0.3 and -6% when compared to MCC but were reduced by about 7, 17 and 21% when compared to MSF, respectively, at the age of 28 days. Inclusion of graphite powder in silica fume concrete increases the rapid chloride penetration (RCP) and reduces the pozzolanic effect of silica fume on cement matrix.

KEYWORDS: Graphite, powder, silica, fume, rapid, chloride, microscopy, concrete.

1. INTRODUCTION

According to annual reports announced by the United Nations, the presence of waste causing environmental problems is likely to increase in the twenty-first century [1]. To fulfill the needs of the population steady increment, urban expansion, and global economic growth, cement production increased from 2.4 billion tons to 4.1 billion tons with an annual increment rate of 2.5% in this decade [2,3]. The cement industry leads to the depletion of natural resources and produces a large carbon footprint, as the cement industry contributes about 5% to 8% of global carbon dioxide CO_2 emissions [4]. To eliminate the harmful impacts of the cement industry, such as global warming and climate change, the Portland cement replacement strategy with supplementary cementitious materials (SMCs) under the name of blended cement is used as an effective method to enhance the sustainability of concrete structures [2,5]. Supplementary cement materials such as silica fume, fly ash, metakaolin and ground granulated blast furnace slag are examples of products of cement industry used as a partially cement replacement, to reduce concrete industry costs and eliminate environmental issues such as pollution [2,3,6]. Although silica fume reduces the workability of concrete, it is widely used among supplementary cementitious materials, as it fills the microstructure of the cement matrix, reacts pozzolanic with calcium hydroxide C–H Ca $(OH)_2$ transforming it into a dense calcium silicate hydrate C–S–H gel, enhances the interfacial transition zone, and consequently improves the mechanical properties [3,7,8]. Ayat *et al*. [9] stated that the substitution of cement with SF with 0% to 20% increases the compressive strengths by about 24.5% and 18.1% at the ages of 7 and 28 days, respectively, for reactive powder concrete. Maria *et al*. [10] found that the improvements in compressive strengths were 24%, 26.5%, and 33.5% at the ages of 7 days, and at 28 days, and were 4%, 16%, and 21.1% for replacement of cement with silica fume by 5%, 10% and l5%, respectively. Edith *et al*. [8] mentioned that the compressive strengths with 5%, 10% and 15% cement replacement by silica fume showed higher values by 13%, 21%, and 15% at the age of 28 days, respectively. The tensile strengths at the age of 28 days are about 9%, 19% and 10% higher than conventional concrete at 5%, 10% and 15% replacement of cement with silica fume, respectively [8]. At 10% replacement of cement with silica fume, the tensile strength was 25% higher than conventional concrete at the age of 28 days [11]. For reactive powder concrete (RPC), when the silica fume content was increased from 0% to 20%, the flexural strength was increased up to 19% compared to conventional concrete. This increment was 6% compared to high-strength concrete HSC [9]. The replacement of cement by 5%, 10% and 10% silica fume increased the 28-day flexural strength by about 3%, 14% and 7%, respectively, compared to conventional concrete [8].

Nowadays, mixing cement, carbon particles, and other additives produces new composite materials with superior chemical and physical properties that advance them to be technologically advanced products [12]. These carbon materials, such as graphite powder, graphite flakes, carbon tubes, and carbon flakes, are added to concrete [12]. The most used carbon additive in electrically conductive concrete (ECC) is the graphite powder (GP) because of its properties such as superior conductivity, chemical stability and low cost [13]. Adding graphite powder to concrete changes the mechanical properties and failure pattern of concrete because of the highly specific surface area, weak cohesion with the cement particles and flakey shape [13]. In 2001, a new type of concrete characterized by electrical conductivity was developed. Graphite powder was used as an inorganic material with high electrical and thermal conductivity [14]. Compared to conventional concrete, the decreases of compressive strengths with 0.5%, 1% and 2.5% cement replacement with graphite powder were 22%, 25% and 9% at the age of 3 days, and 13%, 15% and 2% at the age of 28 days, respectively [15]. The results demonstrated that the compressive strengths of concrete mixes when cement is replaced with graphite powder from 0.3% to 9% were reduced by about 11% to 30% compared to conventional concrete mixes [14]. All available literature on evaluating the behavior of concrete with graphite powder alone as an additive has concluded that graphite powder improves the electrical conductivity of concrete and reduces its mechanical properties [14]. In this study, graphite powder was mixed with a fixed content of silica fume to compensate for deficiency in the mechanical properties of concrete. The objective is to examine the efficacy of graphite powder when combined with a constant amount of silica fume on the mechanical properties of the concrete. Therefore, this work aims to determine the effect of a blind of

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graphite powder and a constant content of silica fume on concrete strengths such as compressive, indirect tension and flexural strengths, as well as rapid chloride penetrability and microstructure of concrete.

2. MATERIALS

2.1. Cement

An ordinary Portland cement (OPC) with a grade of CEM I 42.5 meets the requirements of both E.S.S. 4756 1/2013 CEM I 42.5N [16] and BS EN 197 1:2011 CEM I 42.5N [17] specifications used in this study. Specific gravity and fineness of the cement are 3.13 and 3491 cm^2/gm, respectively, and this comply with both ASTM C204 [18] and ASTM C187 [19], respectively. The actual chemical composition of the cement is mentioned in Table 1.

2.2. Silica Fume SF

A hydraulic blend of active ingredients, silica fume SF, which contains fine latently reactive silicon dioxide with diameter of 0.1 µm [20], was used in this study. The silica fume complies with the requirements of ASTM C-1240 05 [21]. The specific gravity and fineness of silica fume are 2.16 and 18500 cm^2/gm, in accordance with the ASTM C204 [22] and ASTM C187 [19], respectively. The chemical composition of the silica fume is mentioned in Table 1.

2.3. Graphite Powder GP

The graphite powder was obtained by grinding the graphite material in available pencils in the local market. The basic material for pencils is graphite covered with wood or plastic. Graphite is an allotrope form of carbon, which means that it consists only of carbon atoms. The chemical composition of the graphite used in concrete is mentioned in Table 1. The appearance of the mineral materials is shown in Fig. 1.

Table 1: Chemical Composition of Mineral Materials

	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	Na_2O	K_2O	C	L.O.I
Cement	63.12	21.08	4.86	4.43	2.31	1.35	0.30	0.16	-	2.35
Silica Fume	0.17	98.19	0.17	0.38	0.21	0.25	0.15	0.18	-	0.32
Graphite Powder	-	< 0.01	< 0.01	< 0.01	< 0.01	-	-	-	99.5	-

a. Cement **b. Silica Fume** **c. Graphite Powder**

Fig. 1: Physical Appearance of Cement, Silica Fume and Graphite Powder

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2.4. Aggregates

Clean sand and crushed dolomite from Al-Arish city were used as aggregates, agreeing with both ECP 203-2018 [23] and ASTM C33/C33 M18 [24]. The specific gravity and fineness modulus of the sand are 2.66 and 2.28. The nominal maximum size, specific gravity and fineness modulus are 20 mm, 2.52 and 6.67, respectively. Fig. 2 shows the sieve analysis test results of the aggregates.

2.5. Superplasticizer SP

A modified polycarboxylate aqueous solution superplasticizer with a density of 1.08 t/m^3 was used in this experimental work [25]. The superplasticizer meets the stipulations of both ASTM C 494 [26] and BS EN 934 [27].

2.6. Water

A clean, drinkable water was used for casting and curing of the tested concrete samples. The water used meets the requirements of the ECP 203-2018 [23].

3. METHODOLOGY

Components and proportions of concrete mixes are demonstrated in Table 2. Cement, sand, crushed dolomite, and water are constant for all concrete mixes and equal 400, 575, 1151 and 200 kg/m^3, respectively. Silica fume is also constant and it was added to concrete mixes with a replacement level of 10% of the cement content. Graphite powder is the only variable content in concrete mixes which is with replacement ratios of 0%, 2.5%, 5% and 7% of cement. Adding both silica fume and graphite powder to concrete mixes during mixing is done according to ACI 234R [28]. Superplasticizer was added to concrete mixes by 0.8% liter of cement to ensure medium workability [25]. Procedures of the ASTM C192 [29] for preparing, casting, and curing were followed for concrete mix manufacturing.

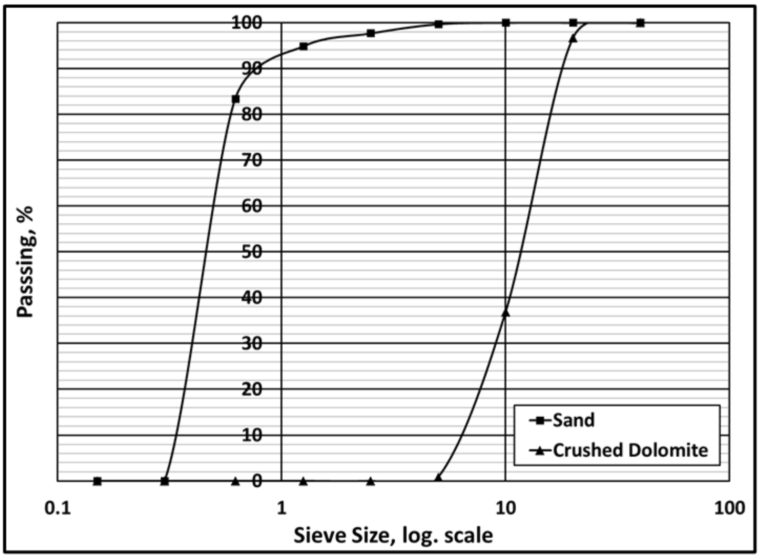

Fig. 2: Sieve Analysis Test Results of Aggregates

The fresh properties of concrete mixes were evaluated by applying a slump test in accordance with ASTM C143 [30]. Hardened properties of the concrete mixes were examined

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by applying compression, indirect tensile and flexural tests. The compressive strengths of the mixes were evaluated by testing concrete cubes with dimensions of 150×150×150 mm in compression tests in accordance with both ECP 203 [31] and ASTM C36 [32]. The indirect tensile strengths of the concrete mixes were evaluated by testing concrete cylinders with dimensions of 300×150 mm in accordance with ASTM C496 [33]. The flexural strengths of the mixes were calculated by testing concrete beams with dimensions of 100×100×500 mm in flexural with accordance with the ASTM C78 [34]. Concrete mixes were tested in the rapid chloride penetration test (RCPT), as the term permeability mostly describes the durability of the material [35]. Procedures of the rapid chloride penetration test comply with the ASTM C1202 [36] and AASHTO T277 [37]. The RCP test was performed on cylinder samples with a diameter of 100 mm and a thickness of 50 mm, which depends on the electrical conductivity of concrete by measuring the amount of current intensity which passes through the tested samples [36,37]. This test is carried out by applying a voltage of 60 volts for 6 hours to samples saturated with water. The amount of electric current intensity is expressed in coulombs. The age of the sample affects the results of the RCP test, which depends on the concrete type and curing procedures, especially concretes containing supplementary materials, as the results of the test decrease at the age of 56 days, and it is preferable to test samples at the age of 90 days [36,37]. Hardened concrete samples with dimensions of 10×10 mm were examined in the scanning electron microscopy (SEM) test to obtain the microstructure of the concrete. The concrete samples were dried in an oven at 105°C for 24 hours in accordance with ASTM C1723-10 [38] and ASTM C1723-16R22 [39].

4. RESULTS

Fig. 3 illustrates the slumps of the concrete mixes. The compressive strengths of the concrete mixes at the ages of 3, 7, 28 and 90 days are illustrated in Fig 4. Both indirect tensile and flexural strengths are illustrated in Figs. 5 and 6, respectively, at the ages of 7 and 28 days. Measured charge passed in Coulombs for concrete mixes and the limitations according to ASTM C1202 [36] and AASHTO T277 [37] are mentioned in Table 3 and are illustrated in Fig. 7 at the age of 90 days. Figs. 8 to 10 show the scanning electron microscopy of concrete mixes.

Table 2: Proportions of the Concrete Mixes

Mix	Mix proportion, Kg/m^3						
	Cement	Sand	Crushed dolomite	Water	Silica fume	Graphite powder	Superplasticizer
MCC	400	575	1151	160	-	-	3.5
MSF	360	575	1151	160	40	-	3.5
MSF-GP2.5	350	575	1151	160	40	10	3.5
MSF-GP5	340	575	1151	160	40	20	3.5
MSF-GP7.5	330	575	1151	160	40	30	3.5

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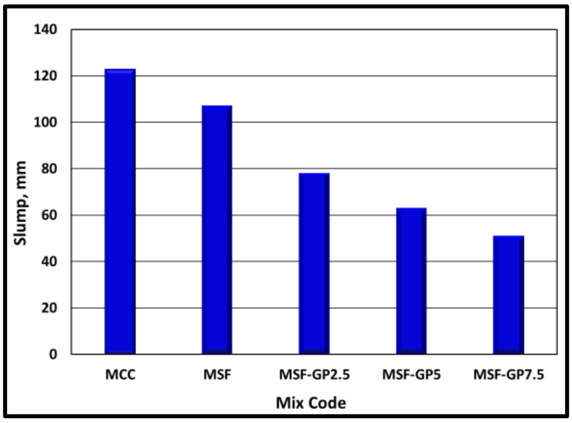

Fig. 3: Slumps of Concrete Mixes

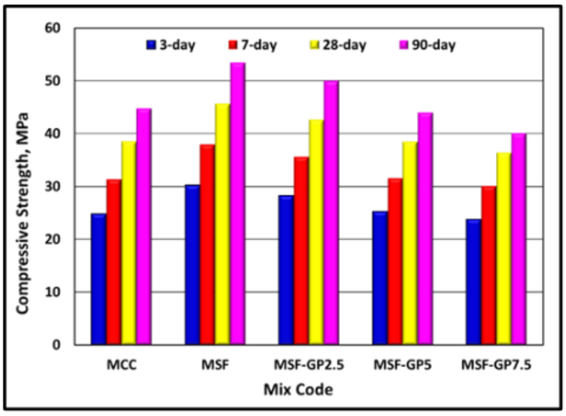

Fig. 4: Compressive Strengths of Concrete Mixes at Ages of 3, 7, 28 and 90 Days

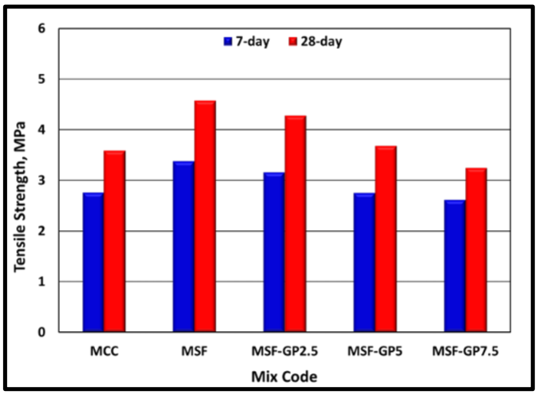

Fig. 5: Tensile Strengths of Concrete Mixes at Ages of 7 and 28 Days

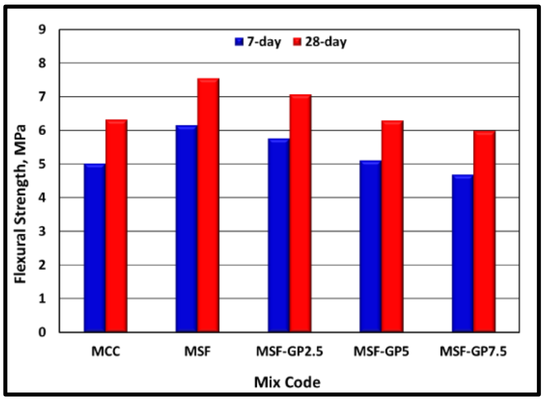

Fig. 6: Flexural Strengths of Concrete Mixes at Ages of 7 and 28 Days

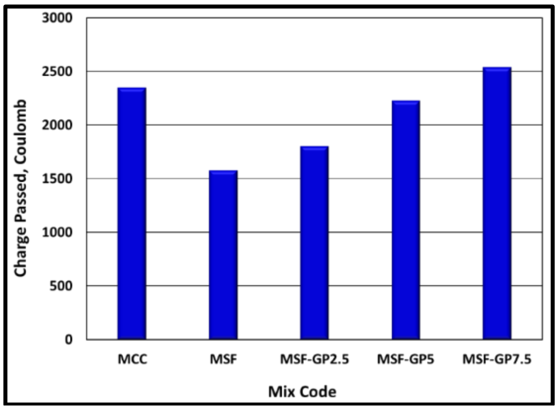

Fig. 7: Charge Passed Through Concrete Samples at Age of 90 Days

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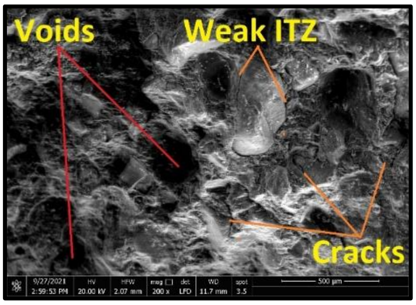
Table 3: Results of Rapid Chloride Penetration RCP Test for Concrete Mixes

Mix ID	Measured Charge Passed (Coulombs)	Standards of ASTM C1202 [36] and AASHTO T277 [37]	
		Charge Passed (Coulombs)	Chloride Ion Penetrability
MCC	2351	2,000 – 4,000	Moderate
MSF	1580	1,000 – 2,000	Low
MSF-GP2.5	1803	1,000 – 2,000	Low
MSF-GP5	2228	2,000 – 4,000	Moderate
MSF-GP7.5	2541	2,000 – 4,000	Moderate



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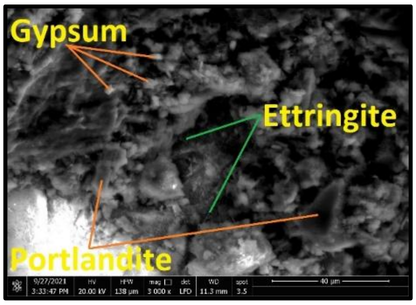
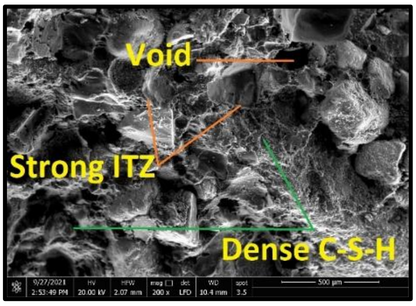


(b)

Fig. 8: SEM Micrographs of Conventional Concrete MC



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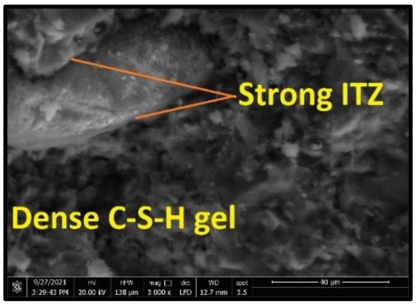

(b)

Fig. 9: SEM Micrographs of Silica Fume Concrete MS10

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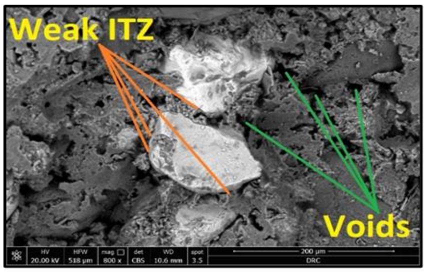

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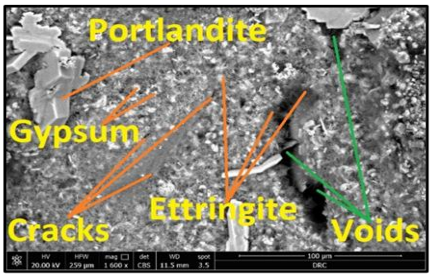

(b)

Fig. 10: SEM Micrographs of Silica Fume Concrete MS10G7.5

5. DISCUSSION

5.1. Slump Test

The slump of mix MSF exhibited a descending tendency of 13% with the existing of 10% cement replacement with silica fume. The surface area of the silica fume increases its siliceous particles attractive forces, which leads to the assemblage of the particles and thus reduces the slump and workability of the concrete [40,41,43]. However, 2.5%, 5% and 7.5% cement replacement with silica fume showed about 37%, 49% and 59% decreases in slump compared to concrete mix MCC. The very high surface area of graphite powder reduces significantly the slump and fluidity of silica fume concrete mixes due to the inter-friction of cement particles and the low hydrophilicity of graphite [15,43].

5.2. Compression Test

It can be seen from Fig. 4 that inclusion of silica fume in concrete increases the compressive strength of concrete. At 10% cement replacement with silica fume, the concrete compressive strength increases by 22%, 21%, 19% and 15% at the ages of 3, 7, 28 and 90 days, respectively, compared to MCC. Incorporation of supplementary cementitious silica fume increases the compressive strength of concrete [44] at all ages [4], as silica fume fills the gaps between cementitious material, which increases the bond strength of the cement particles [45]. Silica fume reduces the breadth and propagation of capillary pores in concrete through its fine particles, which increase the concrete packing density by filling the gaps between larger cement particles, consequently reducing the permeability of concrete [46]. In addition, further calcium silicate hydrate (C-S-H) gel, which is produced by the reaction of calcium hydroxide $Ca\ (OH)_2$ (a byproduct of cement hydration) with silica fume particles restricts, water penetration through the concrete, reduces the pores of the concrete and densifies the cement matrix [10]. The compressive strengths of MSF-GP2.5, MSF-GP5 and MSF-G7.5 were decreased by 6%, 7%, 7% and 7% at the age of 3 days, 16%, 17%, 15% and 18% at the age of 7 days, 21%, 21%, 20% and 24% at the age of 90 days, respectively, compared to MSF.

There were increases of 14%, 13%, 11% and 11% in compressive strengths of silica fume concrete with 2.5% graphite powder content at ages of 3, 7, 28 and 90 days when compared with MCC, and decreases of 6%, 7%, 7% and 8% when compared with silica fume concrete mix MSF, respectively. The use of 5% graphite powder content in silica fume concrete induces an increase in compressive strengths of 2%, 0.6%, –0.3% and –2% compared to MCC, and decreases of 15%, 16%, 18% and 19% compared to MSF at ages of 3, 7, 28 and 90 days,

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respectively. With the replacement of 7.5% graphite powder in silica fume concrete, compressive strength reduced by 4%, 5%, 7% and 9% compared to MCC, and reduced by 19%, 21%, 21% and 24% compared to MSF at the ages of 3, 7, 28 and 90 days, respectively. The compressive strength of concrete decreases with the increase of graphite content [46,47], as the severe decrease in the compressive strength of concrete happens due to the small frictional resistance between materials because of graphite lubrication [47]. Furthermore, the incorporation of graphite powder into concrete results in degradation of cement matrix due to the ongoing weak links between matrix and carbon content of graphite powder [48].

5.3. Indirect Tensile Test

Fig. 5 demonstrates that in comparison with MCC, increments in indirect tensile strengths of 22% and 27% were achieved by incorporating 10% silica fume as partial replacement of cement at ages of 7 and 28 days, respectively. The analysis of results reveals that the incorporation of silica fume enhances the splitting tensile strength of concrete [49] and the optimum increase in splitting tensile strength occurs at a 10% cement replacement level [50]. According to the restriction of micro-cracks, the inclusion of silica fume improves the splitting tensile strength of concrete [51]. The indirect tensile strengths of MSF-GP2.5, MSF-GP5 and MSFGP7.5 are reduced by about 7%, 18% and 22%, and were 6%, 19% and 29%, respectively, at the ages of 7 and 28 days, compared to MSF.

The increases in indirect tensile strength of 2.5% graphite powder replacement silica fume concrete were 14% and 19% at the ages of 7 and 28 days compared to MCC, and these increases turned into decreases of 6% and 7% compared to MSF, respectively. The indirect tensile strengths of silica fume concrete with a replacement level 5% graphite powder were 0% and 3% more than MCC at the ages of 7 and 28 days, respectively, and were 18% and 20% lower than MSF. It can be observed from Fig. 8 that for silica fume concrete incorporating 7.5% graphite powder as partial replacement of cement, the indirect tensile decreased by 5% and 10% at ages of 7 and 28 days compared to MCC and reduced by 22% and 29% compared to MSF, respectively. Increasing the content of graphite powder reduces the tensile strength of concrete [14,52].

5.4. Flexural Test

Fig. 6 demonstrates that incorporating silica fume by 10% as a cement replacement which gave improvements by 23% and 20% at the ages of 7 and 28 days, respectively, compared to conventional concrete mix (MCC). The flexural strength of concrete beams and cubes increases with the increase of silica fume added to the concrete to reach its peak at the age of 28 days [53]; this increment may be more than a double [54]. Incorporation of silica fume into the concrete increases the flexural strength of the concrete because of cement matrix microstructure densification and the further formation of C-S-H gel, which results from the pozzolanic reaction of silica [40]. The flexural strengths of MSF-GP2.5, MSF-GP5 and MSFGP7.5 are reduced by about 6%, 17% and 24%, and were 6%, 17% and 21% at the ages of 7 and 28 days, respectively, compared to MSF. The flexural strengths of silica fume concrete were increased by 15% and 12% for graphite powder replacement level of 2.5% when compared to MCC at the ages of 7 and 28 days, respectively, and were decreased by 7% and 7% compared to MSF. In the same context, silica fume concrete with 5% graphite powder replacement at the ages of 7 and 28 days showed improvements in flexural strengths by about

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2% and 0%, respectively, compared with MCC, and showed a reduction by about 17% and 17% compared with MSF. The flexural strength decrements in MSF-GP7.5, compared to MCC, were found to be 7% and 6% at the ages of 7 and 28 days, respectively. When compared to MSF, these decrements were found to be 24% and 21%. Compared to MCC, the inclusion of graphite powder negatively affects the mechanical properties, such as flexural strength, at different ages of curing [55], where 5% of graphite powder reduces the concrete flexural strength by 55% [56]. Adding graphite powder with a cement replacement level of more than 1% reduces the bond strength of the cement matrix because of decreased adhesion between the graphite particles [57].

5.5. Relationships between Mechanical Properties

Factors of tensile strength to compression strength for MCC, MSF, MSF-GP2.5, MSF-GP5 and MSF-GP7.5 were 0.095, 0.1, 0.1, 0.093 and 0.089, respectively. The tensile strength of silica fume concrete increased as the compressive strength increased, more than the case in the conventional concrete. There was an increment in tensile strength as compressive strength increased only for MSF-GP2.5 when compared to MCC. This increment turned into a decrease for MSF-GP5 and MSF-GP7.5. Factors of flexural strength to compression strength for MCC, MSF, MSF-GP2.5, MSF-GP5 and MSF-GP7.5 were 0.164, 0.165, 0.165, 0.163 and 0.165, respectively. There is no increase or decrease in tensile strength by increasing or decreasing compressive strength by adding silica fume to normal concrete or by adding graphite powder to silica fume concrete.

5.6. Rapid Chloride Permeability RCP Test

Table 3 and Fig. 7 demonstrate the charge passed (coulombs) of the rapid chloride permeability (RCP) test. It justifies the relation between the results obtained and the chloride ion penetration of concrete according to ASTM C1202 [36] and AASHTO T277 [37]. According to the RCP test results, mixes MSF and MSF-GP2.5 have low chloride ion penetrability with 1580 and 1803 Coulomb values, respectively, at the age of 90 days. On the other hand, concrete mixes MCC, MSF-GP5 and MSF-GP7.5 have moderate chloride ion penetrability with 2351, 2228 and 2541 Coulomb values, respectively. The inclusion of silica fume into concrete reduces the chloride ion penetration from the moderate range to the low range, with a reduction of 33% compared to MCC. The use of mineral admixtures such as silica fume in concrete enhances the resistance of rapid chloride permeability (RCP) [58]. The higher the replacement level of cement with silica fume, the lower the total passed chloride charge and the lower the chloride migration diffusion coefficients [58,59,60], because silica fume transforms large pores into fine pores, decreases transition zone micro-cracks [58], and refines the porous structure of concrete [59].

Adding graphite powder to silica fume concrete with a cement replacement ratio of 2.5% decreases the chloride ion penetrability from the moderate range to the low range with a reduction ratio of 24% compared to MCC and an increment of 14% compared to MSF. Incorporation of graphite powder into silica fume concrete with cement replacement level 5% keeps the chloride ion penetrability in a moderate range with a reduction of 5% compared to MCC and an increment of 41% compared to MSF. Inclusion of graphite powder into silica fume concrete with a cement replacement ratio of 10% keeps the chloride ion penetrability in a moderate range with increments of 8% and 61% compared to MCC and MSF, respectively.

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5.7. Scanning Electron Microscopy SEM Test

New phases, such as plate Portlandite (calcium silicate C–H) $Ca(OH)_2$, needle ettringite ($3CaO.Al_2O_3.3CaSO_4.32H_2O$), gypsum ($CaSO_4.2H_2O$), and calcium silicate hydrates C–S–H, are formed after the hydration of cement [61,62]. Some cement hydration components, such as gypsum and ettringite, transform concrete into un-cohesion blocks, cause injurious expansion, and reduce the strength of concrete [61,62]. The interfacial transition zone (ITZ) is a narrow zone between the cement paste and the aggregate, which is characterized by a high porous microstructure filled with large crystals of Portlandite (calcium hydroxide C–H). Therefore, this zone is weaker than the cement paste itself [61,62]. Silica fume enhances the microstructure of concrete, as high pozzolanic activated silica fume particles interact with calcium hydroxide (Portlandite) $Ca(OH)_2$ crystals and turn it into a calcium silicate hydrate C-S-H gel that fills voids, reduces the amount of calcium hydroxide $Ca(OH)_2$, and envelops the needle-shaped ettringite crystals [40,49,63,64]. The function of silica fume does not stop there, as it participates in the reaction of hydrating the concrete, releasing heat, repairing surface cracks in the coarse aggregate, enhancing the strength of bonding between surfaces, reducing porosity, reducing Portlandite C-H content, improving the performance of the concrete microstructure, enhancing the ITZ of concrete, and thus improving the mechanical properties [40,49,63]. Comparing the MCC with graphite concrete samples with cement replacement levels 0.5 and 1%, it was noted that Portlandite C–H and calcium silicate hydrate C–S–H are seen clearly. On the other hand, smaller amounts of both C–H and C–S–H, and larger amounts of both needle-like ettringite and porous microstructure were observed because the amount of C–H has a binding capability greater than CO_2 [65]. The interaction between cement hydration components and graphite crystals yields a weak interfacial transition zone, which evolves a reduction in the mechanical properties of concrete [46]. Figs. 8.a, 9.a and 10.a demonstrate that, comparing to MCC, silica fume concrete MSF shows denser calcium silicate hydrate C–S–H, microstructure with fewer voids, no cracks and stronger ITZ. In contrast, graphite-silica fume concrete MSF-GP7.5 exhibits microstructure with highly voids, more cracks and weaker ITZ. As shown in Figs. 8.b, 9.b and 10.b, graphite-silica fume concrete MSF-GP7.5 contains an excessive amount of abrasion cement hydrate products such as Portlandite, Gypsum and Ettringite compared to MCC. On the other hand, silica fume concrete MSF shows denser calcium silicate hydrate C–S–H. Based on the results of examining the microstructure of concrete mixes by SEM, adding silica fume to concrete improves its mechanical properties, unlike adding graphite powder to silica fume concrete, which leads to a reduction in structural behavior.

6. CONCLUSIONS

This study used three types of concrete samples: traditional concrete, silica fume concrete, and graphite-silica fume concrete. The level of cement replacement with silica fume was 10%, and the ratios of cement replacement with graphite powder were 2.5%, 5%, and 7.5%. The concrete mix specimens were examined in terms of slump, compression strength, indirect tensile strength, flexural strength, rapid chloride permeability (RCP) test, and scanning electron microscopy (SEM) test. The following conclusions were made based on the experimental results.

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1. The slump of concrete is reduced by adding silica fumes to traditional concrete with a cement replacement ratio of 10%. Also, the slump of silica fumes in concrete decreases as the cement replacement ratios with graphite powder increase from 2.5% to 7.5%.
2. Compared to traditional concrete, adding silica fume to concrete with cement replacement level 10% increases compressive strengths by about 22%, 21%, 19% and 15% at the ages of 3, 7, 28 and 90 days, respectively. On the other hand, adding graphite powder with cement replacement levels of 2.5% to 7.5% to silica fume concrete decreases compressive strengths by about 7% to 21%, respectively, compared to silica fume concrete at the age of 28 days.
3. Inclusion of silica fume into concrete with replacement level of 10% increases both indirect tensile and flexural strengths by about 27% and 20%, respectively, at the age of 28 days. In contrast, incorporation of graphite powder into silica fume concrete with replacement levels of 2.5% to 7.5% reduces the indirect tensile and flexural strengths by about 7% to 29% and 7% to 21%, respectively, compared to silica fume concrete at the age of 28 days.
4. Rapid chloride permeability of concrete decreased on addition of silica fume with replacement level 10% because silica fume converts large pores to fine pores, reduces transition zone microcracks, and fills the porous structure of concrete. But rapid chloride permeability of silica fume increases with the increment of graphite powder with replacement level from 2.5% to 7.5%.
5. For the scanning electron microscopy (SEM) Test, silica fume converts Portlandite C–H into denser calcium silicate hydrate C–S–H, exhibits strong interfacial transition zone ITZ, shows fewer microcracks, and improves porosity of concrete. So, silica fume concrete has superior mechanical properties. In contrast, adding graphite powder to silica fume concrete creates a weak interfacial transition zone (ITZ), more microcracks and high-permeable concrete so graphite powder decreases the mechanical properties of concrete.
6. It is recommended to study the structural behavior of graphite powder-silica fume concrete in marine environments and seawater curing.

CONFLICT OF INTEREST

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APPENDIX: LIST OF ABBREVIATIONS

Abbreviation	Stand for (Full Name)
ECC	Electrically conductive concrete
GP	Graphite powder
SCMs	Supplementary cementitious materials
SF	Silica fume
RCP	rapid chloride penetrability
SEM	scanning electron microscopy
MCC	Conventional concrete mix
MSF	Concrete mix with 10% silica fume
MSF-GP2.5	Concrete mix with 10% silica fume and 2.5% graphite powder
MSF-GP5	Concrete mix with 10% silica fume and 5% graphite powder
MSF-GP7.5	Concrete mix with 10% silica fume and 7.5% graphite powder
ITZ	Interfacial transition zone
C–S–H	Calcium silicate hydrates
C–H	Portlandite (calcium silicate)

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