Research Article

Metalized Plastic Waste Fiber Effects on Green Concrete Beams Mechanical Performance

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In a year, millions of forms of plastic are produced, and approximately, half of the generated plastics are used once only. Incorrect and insufficient management of these waste materials causes adverse effects on the nature of the soil, water, humans, and animals’ life. One type of waste plastic is metalized plastic waste (MPW), which is used mainly in different types of food packaging productions, and there is no appropriate technology for reusing it all over the world. In this paper, the effect of MPW as a fiber by 0.5% and 1% on compressive, flexural load capacity, and toughness of green concrete containing 7.5% and 15% silica fume or natural zeolite in Oman Sea tidal zone environment at 28, 90, and 180 days was investigated. The results indicate that by adding the MPW fiber, the compressive strength and maximum flexural load capacity of green concrete were decreased 25% and 15%, respectively. Meanwhile, the effect of MPW fiber on concrete containing 15% silica fume was greater than 7.5% silica fume concrete. Flexural toughness of natural zeolite concrete containing 0.5% MPW fiber was up to 510.9% greater than the observed one. Moreover, the toughness of green concrete containing 1% MPW fiber and zeolite was up to 35% greater than 0.5% MPW concrete. Meanwhile, the effect of MPW fiber on flexural toughness of concrete containing 15% natural zeolite was greater than 7.5% natural zeolite concrete.

1. Introduction

One of the main problems in the world is global warming due to carbon dioxide (CO2) emission as a greenhouse gas [1, 2]. The construction of concrete structures because of cement consumption has important effects on environmental pollution by producing carbon dioxide [3]. Based on previous research, the use of cement for concrete production was accompanied by 522 million tons of CO2 emissions in 2016, so 1000 Kg of cement was equal to 800 Kg of carbon dioxide generation [4, 5]. Therefore, the use of natural Pozzolans such as zeolite or industrial by-products (artificial Pozzolans) such as silica fume is proposed as partial replacements of cement. The utilization of silica fume and zeolite causes a decrease in cement and CO2 emission and improves the mechanical properties of concrete [6, 7]. This type of concrete is known as green concrete. Green concrete is made of different types of materials such as concrete with partial to total replacement of ordinary Portland cement and/or concrete containing waste and recycled materials as aggregate [8]. The by-product of silicon and ferrosilicon alloy production industries is silica fume [9, 10]; at high temperatures from the decrease of quartz, the generation of silica fume happens. In an electric arc furnace, coal, coke, or wood chips with high-purity quartz are heated at a temperature of 2000°C to finish oxygen. Due to the release of quartz to alloy, silicon monoxide vapor will be emitted and is accumulated at the bottom of the furnace. The microspheres of amorphous silica that is known as silicon oxide are the fume that oxidizes and condenses at the high level of the furnace [11]. Silica fume or microsilica has 75% silicon [12, 13].

On the other hand, natural zeolite as a hydrated aluminosilicate has a framework structure. This natural Pozzolan contains channels, cavities, and micropores. Extra-framework cations, a porous framework, and a sorbed phase
(Mx/n[(AlO2)x(SiO2)y]·nH2O) are the important features of zeolite composition. M is extra-framework cations such as Na+, K+, Ca2+, and Mg2+. Variables “n” and “x” are the number of H2O molecules and the valence of M, respectively. Natural zeolites have been utilized for different aims in various areas such as gas filtration, wastewater purification, and concrete structures as a pozzolanic additive and cement replacement [14, 15]. A zeolite has a high level of adsorption capacity (about 40% of its weight [16]) and enhances the durability and permeability of the concrete elements with a low water/binder (w/b) ratio by performance as internal water curing factor [17, 18]. Moreover, concrete containing a natural zeolite has also resistance to sulfate attack and freeze/thaw [19, 20]. Therefore, the need to have green concrete is essential for preserving natural resources, a decrease of environmental pollution, enhancement of the mechanical properties, and durability of concrete structures. The summary of the past research done in the use of zeolite and silica fume in concrete is discussed below.

Bentur et al. [21] found that the compressive strength of concrete containing silica fume as a cement replacement was greater than silica fume as an aggregate replacement in concrete. Sobolev [22] tasted the compressive strength of high-performance concrete. They reported that for decreasing 5% w/b, 10% superplasticizer should be added. Moreover, the maximum compressive strength happened for 15% silica fume. Koksal et al. [23] examined the influence of flexural strength of concrete containing hooked steel fibers and silica fume. They investigated the flexural strength of concrete containing 1% steel fibers was greater than concrete with 0.5 steel fibers. Saridemir [17] evaluated the effect of silica fume and ground pumice on compressive strength and modulus of elasticity of high strength concrete. They concluded that concrete with silica fume could result in lower bleeding and porosity. Mastali and Delvand [24] determined the impact resistance and mechanical properties of fiber reinforced self-compacting concrete (SCC) containing nano-SiO2 and silica fume. They found that the utilization of silica fume as a cement replacement caused improvement in crack resistance. Besides, Poon et al. [25] concluded that concrete with natural zeolite was more effective than fly ash concrete strength. Chan and Ji [26] showed that concrete containing natural zeolite had greater strength than observed ones. On the contrary, with an increase of w/c, concrete strength would be decreased. Ahmadi and Shekarchi [27] reported that diffusion coefficient of 10–20% natural zeolite concrete was decreased. Bilim [28] examined the properties of cement mortars containing zeolite. Investigations showed a reduction in carbonation depth by the use of natural zeolite concrete.

On the other hand, concrete structures are not only dependent on their various materials such as silica fume and zeolite but also are related to the concrete environment such as marine [29, 30]. About 70% of the Earth’s surface consists of water in the forms of marine and oceans [31]. Thus, people in the world directly or indirectly construct the various concrete structures in/near the marines. Concrete structures like a breakwater, groin, seawall, and harbor have better corrosion resistance than other ones such as steel structures for the marine environment [32]. Although marine environments are considered as a positive capacity for the transport industry, marine concrete structures are vulnerable to various physical and chemical deterioration procedures [33]. Atmospheric, submerged, splash, and tidal zones are four exposure situations in maritime structures [34]. Based on previous studies, most aggressive agents such as NaCl, MgCl2, MgSO4, CaSO4, and K2SO4 are in tidal zones. When cracking is occurred by physical and chemical agents, harmful ions penetrate marine concrete structures through the cracks and cause a decrease in the durability and mechanical properties such as the flexural capacity of concrete structures [35, 36]. Therefore, any agent that decreases the amounts of cracks can assist to enhance the flexural capacity, ductility, and durability of various types of concrete structures in the sea environment [37].

Micro- and macrolevel cracks can be arrested by utilizing fibers as reinforcement. Fibers can limit the initiation and growth of cracks at the microlevel and improve toughness and ductility by bridging the cracks from unstable propagation at the macrolevel [38, 39]. Regarding the destructive role of aggressive ions in the marine tidal zone, it seems that the role of fibers in arresting the cracks is bolded in marine concrete structures. Since minimizing the use of nonbiodegradable materials and decrease of waste are potential solutions to a cleaner environment, it is possible to use solid waste materials such as MPW in the forms of fibers in concrete for enhancing the flexural capacity, ductility, and durability of various types of concrete structures in the sea environment. According to global statistics, only in 2014, about 300 million of the various forms of plastic has been produced, and approximately, half of the generated plastics were used once only. According to the massive amount of produced plastic waste, incorrect and insufficient management of these waste materials cause adverse effects on the nature of the soil, water, humans, and animals’ life. One type of waste plastic is MPW films with a thin layer of aluminum, which is used mainly in different types of food packaging productions all over the world. Among various plastic wastes, metalized plastic wastes are improper for reutilizing and there is no appropriate technology for reusing these types of plastic wastes. Therefore, these waste materials are sent to the landfill and then incinerated [40, 41].

Bhogayata and Arora found that concrete containing MPW fiber had a lower compressive strength and workability than the observed one. Jain et al. [42] reported that adding 20% nonmetalized waste plastic bag fiber as natural sand to concrete caused the reduction of the compressive strength by 83%. Mohammadhosseini and Tahir [43] showed that concrete containing up to 0.5% MPW fiber had lower water absorption than simple concrete. Against this background, very few investigations about the flexural behavior of green concrete containing MPW fiber and silica fume/zeolite in the marine environment have been done [44]. It seems that simultaneous use of MPW fiber and silica fume/zeolite as a cement replacement while reducing environmental pollution, decreasing natural resources, and producing green concrete causes to enhance the flexural
2. Materials and Methods

The maximum size of fine and coarse aggregate was 4 and 19 mm, respectively, which were graded based on ASTM C 33. The coarse aggregate was washed for removing dust. The fineness modulus of sand was 2.6. Figure 1 and Table 1 show the curve of particle size distributions of aggregates (grading curve) and properties of aggregates, respectively. The type of ordinary Portland cement was type II by 3.15 specific gravity. The cement replacement materials were silica fume (Si) and natural zeolite (Ze) by 7.5% and 15% cementitious materials by weight.

Table 2 shows the composition of cementitious materials and aggregates. Table 3 presents the physical properties of silica fume and zeolite. The water to cementitious material ratio was 0.4. The MPW fiber type was polypropylene made from food packaging, which was cleaned to prevent any impurities (Figure 2). The MPW fiber volume fractions were 0.5 and 1. Table 4 reveals the properties of MPW fibers. 12 green concrete mixtures were consisting of different replacement materials. The style of concrete mixes was weight basis. Green concrete mix proportions are indicated in Table 5. According to Table 5, for example, Si7.5F0 means beams containing 7.5% silica fume without MPW fiber, or Ze15F0.5 indicates beams containing 15% zeolite with 0.5% MPW fiber. Green concrete mixtures containing no fiber were considered as control mixtures. Specimen preparation, casting, and curing include mixing dry materials and adding water. Then, the superplasticizer was added to the mixture to get the required workability. The green concrete specimens were compacted by a vibrating table. Then, all the specimens were covered with burlap in the casting room for 24 h.

Then, the specimens were demolded and placed in Oman Sea tidal zone environment for 28, 90, and 180 days. Figure 3 shows the samples, which were placed in Oman seawater until 180 days. Figure 4 reveals the samples that are taken out from the Oman Sea. Table 6 shows the main chemical composition of Oman seawater.

Cylindrical specimens with the dimension of 150 × 300 mm were used for testing the compressive strength based on ASTM C39, and beam samples with the dimension of 100 × 100 × 350 mm were used for examining the flexural strength based on BS EN 12390-5: 2009 at 28, 90, and 180 days. Figure 5 reveals the test apparatus for determining the flexural strength.

3. Result and Discussion

The measured values for flexural strength were load and deflections. The calculated parameters were the max of bearing force and fracture toughness at 28, 90, and 180 days. The load-deflection diagram up to the specific deflection such as its maximum is named toughness. The toughness is an energy absorption capacity criterion for the flexural behavior of beams [47]. Since getting a maximum deflection for calculating the toughness of beams containing fiber is not easy, in this paper, the maximum deflection was selected 6 mm for all the beams.

3.1. Effect of MPW Fiber on Compressive Strength of Green Concrete Beams in Oman Sea Tidal Zone. Table 7 shows the compressive strength results of 12 different mixes designing at 28, 90, and 180 days. According to Table 7, the effect of MPW fiber by 0, 0.5%, and 1% on compressive strength of green concrete containing different amounts of silica fume and zeolite is shown in the Oman Sea tidal zone, which is discussed.

3.1.1. Effect of MPW Fiber on Compressive Strength of Green Beams Containing Silica Fume in Oman Sea Tidal Zone. Figure 6 presents the effect of MPW fiber on the compressive strength of green beams containing various amounts of silica fume in the Oman Sea tidal zone at 28, 90, and 180 days.

As can be seen from Table 7 and Figure 6, in Si7.5F0.5, the compressive strength was a maximum of 17.5% lower than Si7.5F0 until 180 days that is because of chemical and physical effects of the contents. Furthermore, adding the 1% MPW fiber to Si7.5F0, the compressive strength reduced 23.9, 22.6, and 19.9 at 28, 90, and 180 days, respectively. It should be noted that in Table 7 and Figure 6, by increasing the age, the amount of compressive strength reduction due to MPW fiber addition was decreased. On the other hand, in green concrete containing 15% silica fume, by addition of 0.5% MPW fiber to Si15F0, the maximum decrease of compressive strength was 25.2% until 180 days. Moreover, in Si15F1, the compressive strength was 17.5%, 14.5%, and 13.4% lower than Si15F0 at 28, 90, and 180 days, respectively. Also, as Table 7 and Figure 6 shows, in this type of green concrete, increasing the age, the value of compressive strength reduction because of MPW fiber addition was decreased.

Reduction of compressive strength might be because of lower bonding and expansion of weak interfacial bonds between the smooth surface of MPW fiber and cement-based materials, redistribution, and increase of voids in cement paste [48, 49]. The utilization of MPW fiber in concrete makes the tortuous network of fibers, which was led to trap the cement particles between the tortuous network of fibers and reduction in hydration activity of cement particles [50, 51]. According to the results from Table 7 and Figure 6, the maximum and minimum compressive strengths of green concrete containing silica fume were related to Si15F0 and Si7.5F1. Moreover, in green concrete containing the same MPW fiber, increasing the amount of silica fume led to the growth of compressive strength. The growth in compressive strength of silica fume concrete might be due to the latent pozzolanic reactions of Si [52]. Furthermore, compressive strength at 180 days to 28 days ratio for green concrete
containing 15% silica fume was greater than 7.5% silica fume concrete. By increasing the amount of silica fume and its filling effect, the bond strength of the cement paste-aggregate interface will be decreased [53, 54].

3.1.2. Effect of MPW Fiber on Compressive Strength of Green Beams Containing Natural Zeolite in Oman Sea Tidal Zone. Figure 7 shows the effect of MPW fiber on compressive strength of green beams containing various amounts of

**Figure 1: Particle size distributions of aggregates [25].**

**Table 1: Properties of aggregates.**

| Aggregate | Water absorption of SSD (%) | Specific gravity (GS) | Maximum size of grains (mm) |
|-----------|-----------------------------|-----------------------|-----------------------------|
| Sand      | 3.10                        | 2.64                  | 5.00                        |
| Gravel    | 2.18                        | 2.45                  | 19.00                       |

**Table 2: Composition of cementitious materials and aggregates.**

| Compound (%) | Cement | Silica fume | Zeolite | Gravel | Sand |
|--------------|--------|-------------|---------|--------|------|
| CaO          | 64.14  | 0.59        | 5.48    | 42.50  | 17.20|
| SiO$_2$      | 22.92  | 92.64       | 68.69   | 8.90   | 50.40|
| Al$_2$O$_3$  | 4.13   | 0.53        | 14.96   | 0.80   | 6.30 |
| Fe$_2$O$_3$  | 2.81   | 1.05        | 3.95    | 1.60   | 6.90 |
| LO.I         | 2.43   | 0.47        | 1.05    | 39.80  | 9.20 |
| MgO          | 1.92   | 1.60        | 1.30    | 5.60   | 6.50 |
| K$_2$O       | 0.85   | 1.64        | 2.12    | 0.20   | 0.80 |
| Na$_2$O      | 0.44   | 0.82        | 1.85    | 0.20   | 2.10 |
| Other        | 0.36   | 0.66        | 0.60    | 0.40   | 0.6  |

**Table 3: Physical properties of silica fume and zeolite.**

| Property                  | Silica fume | Zeolite |
|---------------------------|-------------|---------|
| Bulk density (kg/m$^3$)   | 400         | 450     |
| Specific gravity          | 2.2         | 2.2     |
| Surface area (m$^2$/kg)   | 20000       | 32000   |

containing 15% silica fume was greater than 7.5% silica fume concrete. By increasing the amount of silica fume and its filling effect, the bond strength of the cement paste-aggregate interface will be decreased [53, 54].
natural zeolite in the Oman Sea tidal zone at 28, 90, and 180 days. As can be demonstrated from Table 7 and Figure 7, the addition of 0.5% MPW fiber to Ze7.5F0 caused 15.2, 12.3, and 10.9 decreasing in compressive strength at 28, 90, and 180 days, respectively. Moreover, the compressive strength of Ze7.5F1 was maximum 24% lower than Ze7.5F0 at
180 days. It is clear from Figure 7 that the amount of compressive strength decreasing due to MPW fiber addition reduced by growth the age.

Also, the compressive strength of Ze15F0.5 was maximum 17.5% lower than Ze15F0. Furthermore, by adding 1% MPW fiber to Ze15F0, the compressive strength was decreased 21.8%, 23.9%, and 24.8% at 28, 90, and 180 days, respectively. It should be noted that in Figure 7, by increasing the age, the amount of compressive strength reduction because of MPW fiber addition was decreased.

The main reason for lower compressive strength in green concrete containing MPW fiber may be due to the increase of pores in green concrete. Usually, the existence of MPW fiber in green concrete can lead to creating a weak zone within cracks development and, finally, a reduction in the compressive strength of concrete [55]. According to

Table 6: Main chemical composition of Oman seawater.

| Chemical      | NaCl   | MgCl₂ | Na₂SO₄ | CaCl₂ | KCl   | NaHCO₃ | KBr   |
|---------------|--------|-------|--------|-------|-------|--------|-------|
| Concentration (g/L) | 26.90  | 5.20  | 3.80   | 1.36  | 0.655 | 0.261  | 0.155 |

*Chemicals at concentrations below 0.1 g/L are not included.

Figure 4: Samples after taking out from the Oman Sea.

Table 6: Main chemical composition of Oman seawater.

Figure 5: Test apparatus for determining the flexural strength.
Table 7: Compressive strength results (MPa).

| Mix        | Days 28 | Days 90 | Days 180 |
|------------|---------|---------|----------|
| Si7.5F0    | 34.6    | 36.3    | 38.9     |
| Si7.5F0.5  | 28.5    | 31.1    | 33.7     |
| Si7.5F1    | 26.3    | 28.1    | 31.2     |
| Si15F0     | 39.4    | 44.6    | 45.2     |
| Si15F0.5   | 30.3    | 33.4    | 36.8     |
| Si15F1     | 28.3    | 32.1    | 34.0     |
| Ze7.5F0    | 29.8    | 33.7    | 36.1     |
| Ze7.5F0.5  | 25.3    | 29.5    | 32.2     |
| Ze7.5F1    | 23.3    | 25.6    | 27.7     |
| Ze15F0     | 31.9    | 36.6    | 37.5     |
| Ze15F0.5   | 26.3    | 32.3    | 34.5     |
| Ze15F1     | 24.9    | 27.9    | 28.2     |

Figure 6: The compression of green concrete compressive strength containing zeolite with/without MPW fiber.

Figure 7: The compression of green concrete compressive strength containing zeolite with/without MPW fiber.
Table 8 shows the effect of MPW fiber on flexural behavior of green concrete containing silica fume in Oman Sea Tidal Zone. Comparing the green concrete containing two equal amounts of MPW fiber and cement replacement, silica fume concrete had higher amounts of compressive strength than natural zeolite concrete. It could be related to the higher Pozzolanic activity of silica fume than natural zeolite because of finer particles. Moreover, silica fume has more amount of reactive SiO2 [57, 58]. On the other hand, based on previous studies, zeolite concretes have higher porosity than silica fume [59]. Factors such as higher Pozzolanic activity, more amount of reactive SiO2, and lower porosity in concrete containing silica fume are bolded in the marine tidal zone. Since chloride and other harmful ion penetrations are related to amounts of porosity and permeability of concrete, further reduction in growth of green concrete flexural toughness [39].

Based on definitions in previous sections in this paper and ductility concept, the load-deflection diagram up to the specific deflection such as its maximum is named toughness. The toughness as a factor to determine the ability of elements to absorb energy is calculated from the area under the load-deflection diagram to special deflection. According to Figures 8–10, in concrete containing 7.5% silica fume without MPW fiber, by adding 0.5% MPW fiber, the toughness was increased by 394.5%, 425.6%, and 432% at 28, 90, and 180 days, respectively. Moreover, flexural toughness of Si7.5F1 was maximum of 603.8% higher than Si7.5F0, which was related to 180 days. It should be noted that the addition of 0.5% MPW fiber to Si7.5F0.5 caused the increase by maximum of 32% in toughness at 180 days. Also, in Si15F0 specimens, the addition of 0.5% MPW fiber caused the maximum increase of toughness by 459.8%, which was referred to 180 days of age. Furthermore, the toughness of Si15F1 was 580%, 666.2%, and 712.2% more than Si15F0 at 28, 90, and 180 days, respectively. Besides, the addition of 0.5% MPW fiber to Si15F0.5 caused an increase by maximum of 45% in toughness at 180 days.

Generally, at both micro- and macrodimensions, the utilization of fibers in concrete can be efficient in arresting the cracks. The beginning and expansion of cracks are prevented by the fibers at the microlevel. Fibers can make mechanisms that provide effective bridging and decrease the rate of crack growth after the microcracks link together and changed to macrocracks. Therefore, the mentioned mechanism can lead to enhance the toughness and ductility [61].

Figure 7, the compressive strength of Ze15F0 and Ze7.5F1 was maximum and minimum, respectively. Moreover, in green concrete containing the same MPW fiber, growth of compressive strength was related to increasing the amount of zeolite. Further reduction of calcium hydroxide of the hydrated cement paste because of Pozzolanic reactions and filler effect of natural zeolite lead to improvements in the microstructure and transition zone of green concrete and finally the compressive strength [56]. Furthermore, compressive strength at 180 days to 28 days ratio for green concrete containing 15% zeolite was approximately the same as 7.5% zeolite concrete.

3.2. Effect of MPW Fiber on Flexural Behavior of Green Concrete Beams in Oman Sea Tidal Zone.

3.2.1. Effect of MPW Fiber on Flexural Behavior of Silica Fume Concrete Beams in Oman Sea Tidal Zone. The flexural behavior of concrete beams containing silica fume without/with MPW fiber in Oman Sea tidal zone at 28, 90, and 180 days is shown in Figures 8–10, respectively. As been mentioned in past sections, the maximum displacement (deflection) was considered 6 mm for all the beams. As can be seen from Figures 8–10, in concrete containing 7.5% silica fume, the maximum of load capacity was related to Si7.5F0, while by addition of 0.5% MPW fiber, the maximum of load-bearing was decreased 16%, 14%, and 10% at 28, 90, and 180 days, respectively. On the other hand, the addition of 1% MPW fiber to Si7.5F0 reduced the maximum load capacity up to 23%, which was related to 28 days. Furthermore, the maximum load-bearing for 15% silica fume concrete was Si15F0.5 by 23%, 21%, and 11% lower than Si15F0 at 28, 90, and 180 days, respectively. Also, adding 1% MPW fiber to Si15F0 caused a maximum reduction by 29% maximum of the load capacity value of in silica fume concrete. The reduction of maximum load capacity might be because of this reason that since the amount of maximum load-bearing mostly depends on cement paste matrix properties, at early ages, concrete containing more silica fume due to faster cement hydration and lower workability is susceptible to more cracking and high porosity. Thus, at early ages, the addition of MPW fiber causes further porosity and more reduction of maximum load capacity. By increasing the age, completing the hydration process, reduction of porosity, and increasing the integrity of concrete, reduction in maximum load-bearing values due to MPW fiber addition is decreased [60].

The toughness as a factor to determine the ability of elements to absorb energy is calculated from the area under the load-deflection diagram to special deflection. According to Figures 8–10, in concrete containing 7.5% silica fume without MPW fiber, by adding 0.5% MPW fiber, the toughness was increased by 394.5%, 425.6%, and 432% at 28, 90, and 180 days, respectively. Moreover, flexural toughness of Si7.5F1 was maximum of 603.8% higher than Si7.5F0, which was related to 180 days. It should be noted that the addition of 0.5% MPW fiber to Si7.5F0.5 caused the increase by maximum of 32% in toughness at 180 days. Also, in Si15F0 specimens, the addition of 0.5% MPW fiber caused the maximum increase of toughness by 459.8%, which was referred to 180 days of age. Furthermore, the toughness of Si15F1 was 580%, 666.2%, and 712.2% more than Si15F0 at 28, 90, and 180 days, respectively. Besides, the addition of 0.5% MPW fiber to Si15F0.5 caused an increase by maximum of 45% in toughness at 180 days.

Generally, at both micro- and macrodimensions, the utilization of fibers in concrete can be efficient in arresting the cracks. The beginning and expansion of cracks are prevented by the fibers at the microlevel. Fibers can make mechanisms that provide effective bridging and decrease the rate of crack growth after the microcracks link together and changed to macrocracks. Therefore, the mentioned mechanism can lead to enhance the toughness and ductility [61].

On the other hand, the toughness of Si7.5F0, Si7.5F0.5, and Si7.5F1 from the age of 28 days to 180 days grew 12%, 21%, and 29%, respectively. In addition, in this range of time, the flexural toughness of Si15F0, Si15F0.5, and Si15F1 was increased 17%, 28%, and 39%, respectively. In the lower ages, there is a thick and weak transition zone with a lot of porosity between fibers and the paste, which may lead to reduction in growth of green concrete flexural toughness [39].

According to obtained results in Table 8, the toughness of Si7.5F0 and Si7.5F1 was maximum and minimum, respectively. Moreover, in green concrete containing the same MPW fiber, growth of compressive strength was related to increasing the amount of zeolite. Further reduction of calcium hydroxide of the hydrated cement paste because of Pozzolanic reactions and filler effect of natural zeolite lead to improvements in the microstructure and transition zone of green concrete and finally the compressive strength [56]. Furthermore, compressive strength at 180 days to 28 days ratio for green concrete containing 15% zeolite was approximately the same as 7.5% zeolite concrete.

Table 8 shows the effect of MPW fiber on flexural behavior of green concrete containing silica fume in Oman Sea Tidal Zone. Comparing the green concrete containing two equal amounts of MPW fiber and cement replacement, silica fume concrete had higher amounts of compressive strength than natural zeolite concrete. It could be related to the higher Pozzolanic activity of silica fume than natural zeolite because of finer particles. Moreover, silica fume has more amount of reactive SiO2 [57, 58]. On the other hand, based on previous studies, zeolite concretes have higher porosity than silica fume [59]. Factors such as higher Pozzolanic activity, more amount of reactive SiO2, and lower porosity in concrete containing silica fume are bolded in the marine tidal zone. Since chloride and other harmful ion penetrations are related to amounts of porosity and permeability of concrete, further enhancement in cement matrix by silica fume causes reduction of porosity and permeability of concrete.

3.1.3. Compare the Effect of MPW Fiber on Compressive Strength of Concrete Containing Natural Zeolite and Silica Fume in Oman Sea Tidal Zone. Comparing the green concrete containing two equal amounts of MPW fiber and cement replacement, silica fume concrete had higher amounts of compressive strength than natural zeolite concrete. It could be related to the higher Pozzolanic activity of silica fume than natural zeolite because of finer particles. Moreover, silica fume has more amount of reactive SiO2 [57, 58]. On the other hand, based on previous studies, zeolite concretes have higher porosity than silica fume [59]. Factors such as higher Pozzolanic activity, more amount of reactive SiO2, and lower porosity in concrete containing silica fume are bolded in the marine tidal zone. Since chloride and other harmful ion penetrations are related to amounts of porosity and permeability of concrete, further enhancement in cement matrix by silica fume causes reduction of porosity and permeability of concrete.
Table 8: Maximum load capacity ($P_{\text{max}}$) and flexural toughness ($T^*$) results.

| Mix    | 28 (days) | 90 (days) | 180 (days) | 28 (days) | 90 (days) | 180 (days) |
|--------|-----------|-----------|------------|-----------|-----------|------------|
| Si7.5F0| 14.9      | 16.6      | 18.0       | 2.0       | 2.1       | 2.2        |
| Si7.5F0.5| 12.8     | 14.6      | 16.4       | 9.8       | 10.8      | 11.8       |
| Si7.5F1| 12.1      | 13.8      | 15.9       | 12.1      | 14.3      | 15.7       |
| Si15F0 | 16.5      | 19.1      | 19.6       | 2.2       | 2.3       | 2.6        |
| Si15F0.5| 13.4     | 15.8      | 17.6       | 11.1      | 12.6      | 14.3       |
| Si15F1 | 12.8      | 15.4      | 17.1       | 14.9      | 17.6      | 20.7       |
| Ze7.5F0| 13.3      | 15.0      | 16.8       | 2.1       | 2.2       | 2.4        |
| Ze7.5F0.5| 11.8    | 13.5      | 15.6       | 7.9       | 9.5       | 10.9       |
| Ze7.5F1| 11.1      | 12.8      | 15.00      | 9.7       | 11.7      | 13.6       |
| Ze15F0 | 14.0      | 16.6      | 18.1       | 2.4       | 2.5       | 2.8        |
| Ze15F0.5| 11.8     | 14.1      | 16.6       | 8.8       | 10.8      | 12.5       |
| Ze15F1 | 11.5      | 14.0      | 16.0       | 11.6      | 14.1      | 16.8       |

*$P_{\text{max}}$: Maximum of load capacity/bearing. $T^*$: Flexural toughness

Figure 8: Effect of MPW fiber on flexural behavior of concrete containing silica fume at 28 days.

Figure 9: Effect of MPW fiber on flexural behavior of concrete containing silica fume at 90 days.
180 days, the flexural toughness increased by 15%, 21%, and 32%, respectively. Absolutely, the amount of growth in toughness before 180 days was lower.

The positive effects of silica fume additions might be related to considerable pore modification such as changing the bigger pores into smaller ones because of their pozzolanic reaction at the same time as with cement hydration. Moreover, by adding the silica fume, capillary porosity, which is caused by reaction products such as calcium silicates and calcium aluminates, is decreased and density is increased. Thus, the bonding between MPW fibre and cement matrix is increased [62]. As shown in Figures 8–10, the difference among diagrams was clearer at 180 days. This could be attributed to have been caused by increasing the age, completing the hydration process, and increasing the bonding between cement-based materials and MPW fiber [61]. Also, in concrete without MPW fiber, the amount of deflection related to the maximum load capacity was decreased from 28 days to 180 days. On the contrary, in concrete containing MPW fiber, this special deflection was increased from 28 days to 180 days.

3.2.2. Effect of MPW Fiber on Flexural Behavior of Natural Zeolite Concrete Beams in Oman Sea Tidal Zone.

Figures 11–13 represent the flexural behavior of zeolite concrete beams containing without/with MPW fiber in Oman Sea tidal zone at 28, 90, and 180, respectively. As shown in Figures 11–13, among 7.5% zeolite concrete, the higher load-bearing was related to Ze7.5F0, which was decreased 13%, 11%, and 8% by the addition of 0.5% MPW fiber, at 28, 90, and 180 days, respectively. Moreover, by adding 1% MPW fiber to Ze7.5F0, the maximum load capacity decreased up to 19%, which was referred to 28 days.

Furthermore, the maximum load-bearing for concrete containing 15% zeolite was Ze15F0.5, which was 19%, 18%, and 10% lower than Ze15F0 at 28, 90, and 180 days, respectively. Also, in maximum load capacity, the addition of 1% MPW fiber to Ze15F0 led to maximum reduction by 21%, which was related to 28 days. Since the dependence of maximum load-bearing on cement-based materials properties, at early ages, concrete containing more zeolite due to finer grading has lower workability, more cracking, and high porosity. The porosity and high active phase (SiO2 and Al2O3) in zeolite are noticeable. Therefore, the improvement of the microstructure of hardened cement paste and concrete is predictable. Nonetheless, when the amount of natural zeolite is increased, the porosity of concrete is grown remarkably. Those positive effects on the microstructure of the paste then could not be great enough to mitigate the negative effects. Thus, at early age, the addition of MPW fiber leads to more porosity and reduction in maximum load capacity. By the growth of the age, reduction in maximum load capacity because of MPW fiber addition is decreased because of more perfecting the hydration of cement, decrease of porosity, and, finally, increasing the integrity of concrete [60, 63].

Considering Figures 11–13, 7.5% zeolite concrete containing 0.5% MPW fiber had 273.6%, 336.8%, and 363.1% higher toughness than Ze7.5F0 at 28, 90, and 180 days, respectively. Furthermore, flexural toughness of Ze7.5F1 was maximum of 478.8% higher than Ze7.5F0, which was referred to 180 days. It was clear that by adding 0.5% MPW fiber to Ze7.5F0.5 the toughness was increased by maximum of 25% at 180 days. Also, Ze15F0.5 had greater toughness than Ze15F0 by 354.2%, which was related to 180 days of age. Moreover, flexural toughness of Ze15F1 was 385.7%, 463.2%, and 510.9% more than Ze15F0 at 28, 90, and 180 days, respectively. Besides, Ze15F1 had higher toughness than Ze15F0.5 by maximum of 35% at 180 days. This could be due to the fibers’ ability to bridge and arrest the cracks, resisting tensile forces, and enhancing the ductility of concrete beams containing natural zeolite, which showed improved postcracking behavior. Meanwhile, by increasing the age, flexural toughness because of bonding between cement paste matrix and MPW fiber is increased as demonstrated in Figures 11–13 [64].
Figure 11: Effect of MPW fiber on flexural behavior of concrete containing zeolite at 28 days.

Figure 12: Effect of MPW fiber on flexural behavior of concrete containing zeolite at 90 days.

Figure 13: Effect of MPW fiber on flexural behavior of concrete containing zeolite at 180 days.
On the other hand, the toughness of 180 days to 28 days ratios for Ze7.5F0, Ze7.5F0.5, and Ze7.5F1 were 1.11, 1.37, and 1.41, respectively. In addition, in the range of 28 days to 180 days, flexural toughness of Ze15F0, Ze15F0.5, and Ze15F1 was increased 16%, 41%, and 45%, respectively. Based on achieved results in Table 8 and Figures 11–13, in concrete containing an equal amount of MPW fiber, increasing the amount of zeolite the same as silica fume caused a higher toughness. According to the received results, in concrete containing 0%, 0.5%, and 1% MPW fiber, by growth amount of zeolite from 7.5% to 15% at 180 days, the flexural toughness increased by 17%, 15%, and 23%, respectively. It was clear that the amount of increase in toughness before 180 days was lower. This enhancement can be due to the formation of the second C–S–H because of Pozzolanic reactions, consumption and drop of Portlandite, and more adhesion of cement paste. Meanwhile, also filler impact of natural zeolite leads to improving the microstructure and transition zone. According to the dependence of flexural behavior sensitivity on porosity and transition zone properties, structural configuration of the transition zone, and the existence of calcium hydroxide crystals, it can be said that natural zeolite improved the transition zone structure through consuming Portlandite crystals and forming secondary C–S–H. Thus, the porosity is reduced and the bonding fiber-cement paste matrix, as well as flexural toughness, is increased [65]. As can be seen in Figures 11–13, the difference among curves was distinct at 180 days. This could be related to perfecting the hydration cement process and improving the bonding between cement-based materials and MPW fiber [61]. Moreover, in plain concrete without MPW fiber, the amount of displacement referred to the maximum load-bearing was decreased from 28 days to 180 days. Conversely, in MPW fiber concrete, this special displacement grew from 28 days to 180 days.

3.2.3. Compare the Effect of MPW Fiber on Flexural Behavior of Concrete Beams Containing Natural Zeolite and Silica Fume in Oman Sea Tidal Zone. According to the results shown in Table 8, in green concrete without MPW fiber, exchanging the 7.5% natural zeolite to silica fume led to increase in maximum load capacity by 12%, 10%, and 7% at 28, 90, and 180 days, respectively. Moreover, in green concrete containing 0.5% MPW, the same as 1% MPW, replacing 7.5% zeolite with silica fume caused an increase in maximum load-bearing by 9% maximum, which related to 28 days. On the other hand, in concrete with no MPW fiber, substituting the 15% natural zeolite with silica fume led to growth in maximum load capacity by 18%, 15%, and 8% at 28, 90, and 180 days, respectively. Furthermore, in green concrete containing 0.5% MPW, approximately the same as 1% MPW, exchanging 15% zeolite to silica fume caused an increase in maximum load-bearing by 14% maximum, which referred to 28 days. As shown in Table 8, in green concrete without MPW fiber, replacing the 7.5% natural zeolite with silica fume led to increasing the toughness by 10%, 12%, and 15% at 28, 90, and 180 days, respectively. This might be because of the concrete containing silica fume has more impact on improving the structural properties of concrete than natural zeolite concrete at the equaled level of cement-based replacement. This can be attributed to the higher pozzolanic reactivity of silica fume compared to natural zeolite because of finer particles and more amount of reactive SiO2. Green concretes containing silica fume have the lowest porosity because they have fewer capillary pores [66]. Moreover, in green concrete containing 0.5% MPW and 1% MPW, at 180 days, exchanging 7.5% zeolite to silica fume caused an increase in flexural toughness by 21% and 32%, respectively.

It was clear that the amount of growth in toughness until 180 days was been lower. Furthermore, in green concrete without MPW fiber, substituting the 15% natural zeolite with silica fume led to increasing the toughness by 12%, 15%, and 17% at 28, 90, and 180 days, respectively. Moreover, in green concrete containing 0.5% MPW and 1% MPW, at 180 days, replacing 15% zeolite with silica fume caused an increase in flexural toughness by 15% and 23%, respectively. It should be noted that the amount of growth in toughness until 180 days has been lower. Agents such as more pozzolanic activity, higher amount of reactive SiO2, and lower porosity in green concrete containing silica fume than natural zeolite concrete are more important in the marine tidal zone. Based on previous studies, since the resistance against the chloride and other harmful ions penetration in silica fume concrete is considerably more than natural zeolite concrete, the lower permeability and deterioration, as well as higher toughness and ductility in green concrete containing silica fume, are predictable [66].

4. Conclusion

In this study, the effect of 0.5% and 1% MPW fiber on compressive strength and flexural behavior of green concrete containing 7.5% or 15% silica fume or natural zeolite in tidal zone environment of Oman Sea at 28, 90, and 180 days was investigated and compared. Meanwhile, the green concrete without MPW fiber was considered as an observed specimen. In green concrete containing silica fume or natural zeolite, by addition of MPW fiber, the compressive strength was up to 25% decreased. However, at the equaled dosage of MPW fiber, the compressive strength of silica fume concrete was greater than zeolite concrete. Maximum flexural load capacity for green concrete containing MPW fiber was up to 15% lower than the observed specimens. Adding the 0.5% MPW fiber to observed concrete containing different dosages of silica fume caused up to 712.2% increase in flexural toughness. Moreover, green concrete containing 1% MPW fiber was up to 45% greater than 0.5% MPW concrete. On the contrary, the effect of MPW fiber on flexural toughness of green concrete without MPW fiber was so much. However, the toughness of green concrete containing 1% MPW fiber was up to 35% and 45% greater than 0.5% MPW concrete containing silica fume and natural zeolite, respectively. Moreover, MPW fibers were more compatible with silica fume in green concrete. The effect of MPW fiber on flexural toughness of silica fume concrete was greater than natural zeolite concrete.
Data Availability
Requests for access to these data should be made to the corresponding author (h.safayanikoo@cmu.ac.ir).

Conflicts of Interest
The author declares that there are no conflicts of interest regarding the publication of this paper.

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