Water abrasion and drop-mass impact of mono and hybrid steel fiber-reinforced reactive powder concrete

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Abstract. In addition to strength, the durability of concrete is a major characteristic to measure its quality. Abrasion and accidental impacts are types of loads that negatively influence the strength and durability of concrete. This article aims to compare the water-impact and drop-mass impact resistances of reactive powder concrete (RPC). Three mixtures of RPC were prepared to evaluate their abrasion resistance using the water jet method in addition to their impact resistance using the repeated drop-mass impact test based on the ACI 544-2R repeated impact procedure. All of the three mixtures have same material properties and a fiber content of 2.5% by volume. One of them contains steel fiber with length of 6 mm, the second contains 15 mm steel fiber, and the last one contains a combination of 15 and 6 mm steel fibers. The experimental work results showed that the mixture contains 15 mm steel fibers showed the best abrasion and impact resistances, while the combination of 15 and 6 mm steel fibers showed the lowest impact resistance and the lowest abrasion resistance at the first six hours. The resulted compressive strength values were close, but that of the sample contains 15 mm fibers was the highest.

Keywords: Concrete, abrasion, drop-mass impact, steel fiber, hybrid fiber.

1. Introduction
One of the most important considerations in the structural design is the span life, where the design life span of particular strategic structures can be over 100 years. The challenge is to keep the structure safe and works with its full functionality during the whole period of service life by producing new durable materials that can resist different loading types. In hydraulic structures like dams, the abrasion damage, which is the gradual decrement in the depth of the member due to the persistent peeling of the upper concrete surface by the friction and impact actions of the water and water-borne particles, should be well considered as it imposes high risks and valuable cost for maintenance [1-5]. The surfaces of the hydraulic structure members that exposed to the effects of the very rapid water flow should be studied well since they are exposed to two types of abrasion damages, one of them is horizontal that is affected by the parallel movement of water and the carried particles, such as sand, gravel, rocks, debris, etc., on the surface causing erosion in the top concrete layers. On the other hand,
the vertical impact of the water and water-borne solids on the structure members subject impact abrasion loads and that requires concrete with high impact resistance [6-11]. The impact load is mostly a sort of an accidental load, while in some cases it is calculated among the structural design loads [12-13]. Many types of structures can be effected by the drop-mass or projectile impact loads such as in a war region, where structures can be exposed to explosions or rigid pavements in airports that are effected by airplanes landing [14-18]. In literature, many tests were directed for evaluating both abrasion and impact resistant of concrete. The ASTM C1138 method was used to evaluate the abrasion resistance [19-20], others used the water-jet method [23-29], which was first suggested by Liu et al. [30]. For testing the impact resistance, several methods were proposed such as the Charpy pendulum method, explosive method, projectile method and drop-weight method [17, 31, 32]. For fiber-reinforced concrete samples, ACI 544-2R recommended to use the facilitated drop-weight impact procedure [33]. This test can be used simply in the laboratory by hitting the concrete specimens by a repeated impact load. The mean value of at least six specimens must be determined to represent the impact resistance of the tested sample according to ACI 544-2R [34-40].

The development of concrete materials is required to produce a high strength, durable and ductile concrete that is economically and environmentally friendly. Several types of concrete were developed in the last of decades, for instance, self-consolidating concrete (SCC), high-performance concrete (HPC), ultra-high-performance concrete (UHPC), engineered cementitious composites (ECC), and self-sensing concrete. The development of durable and ductile concrete attributes to enhance the resistance of concrete for accidental loads such as the impact load. Reactive powder concrete (RPC) is newly developed concrete that consists of large quantities of cementitious materials, fine filler materials, and sufficient content of fibers. In literature, there are many studies on the abrasion and impact resistance of different types of concretes. However, the authors couldn’t find studies that compare the wearing and impact resistances of RPC using hybrid fiber reinforcement. Therefore, the aim of this study is to enrich the literature by making comparisons between the effects of the abrasion impact and the drop-mass impact loads.

2. Methodology

2.1. Testing apparatus

In this study, a comparison between the abrasion due to water impact and the drop-mass impact resistances of RPC specimens was studied. Thus, two different apparatuses were used. Figure 1 shows the details of the used abrasion apparatus. Abid et al. [7] manufactured this device to perform the water impact test with different angles using the originally recommended [30] rectangular water orifice, the dimension of this orifice was 200 mm long, and 10 mm wide. In the current tests, a circular orifice with 50 mm diameter was used, the angle between the water impact direction and the sample was 90°. The test must be continued for six hours divided to six one-hour steps. The sample should be weighted prior and post each step to evaluate the loss of the weight by abrasion [30], while in this study, the test was continued for 12 hours instead of the originally recommended 6 hours. Hence, the time step became two hours instead of 1 hour. The reason of this extension of time period was to obtain clearer test results. The capacity of the tank is 1 m³ of water. The external dimensions of the frame base were 2000×750 and its height was 150 mm, the water was mixed with 30 kilograms of sand with sizes ranged between 0.3 to 3.35 mm to simulate the abrasive materials in water.

The second testing device was the repeated drop-mass impact test apparatus that complies with ACI 544-2R recommended procedure [33]. This test is a very low-cost test procedure to determine the impact resistance of the concrete that contains fibers without the need to use sophisticated electronic sensors and techniques. The procedure recommended by ACI 544-2R uses a mass of 4.5 kilograms, it falls freely on the disk specimen from a vertical distance of 450 mm. There should be a steel ball with a diameter of approximately 63 mm on the center of the sample surface to transform the impact load to the sample, which is fixed in the designed position by a steel ring. During the test, the number of hits should be recorded two times, the first is after the appearing of the first crack, while the second time is at the failure. However, along the test, the specimen should be fixed by four steel lugs and rubber pieces. When the first crack appears, the rubber pieces must be removed to allow for a free failure,
where the number of blows must be recorded when the specimen divides into two or more pieces and touches the steel lugs from two or three sides [33]. In this study, the used falling-mass was 10 kg instead of the standard 4.5 kg, and the falling-high was 700 mm instead of the 450 mm. Basically, the tested RPC sample contains high amount of cementitious material and fibers; therefore, the time and the number of blows required to fail the specimen were very high. The main goal of these alterations was to save the time and reduce the efforts as the test is directed manually. Moreover, for the same reason, the diameter of the specimens was decreased to 125 mm instead of 150 mm but the standard thickness was kept 65 mm. Figure 2 shows a sketch for the used impact device.

2.2. Materials and mixtures

Three RPC mixtures were prepared, two lengths of brass coated straight micro-steel fibers were added, one was of 6 mm and the other was of 15 mm length. The mix properties for all of the three mixtures were the same and the fiber content was also the same, which was 2.5% by volume but with various fiber combinations as listed in Table 1. The first group was SF6, it contained the first type of fibers only, while the second group was SF15, which contained fibers with a length of 15 mm, the last one was SF6-15, it involved a quantity of 1.25% from each of the used micro-steel fibers. The properties of the used steel fibers are listed in Table 2.

As shown in Table 3, three types of cementitious materials; cement, fly ash, and silica fume were mixed, while silica sand was used as a filler. Low amount of water and large quantity of fibers were added. The particle size of silica sand was between 0.08 to 0.2 mm with 1500 kg/m³ dry density.
Portland cement type 42.5R was utilized with a specific gravity of 3.15 and a specific surface of 362 \(m^2/kg\), while the other properties as given in Table 4. On the other hand, 2.2 was the specific gravity for both silica fume and fly ash. The specific surface of the silica fume was 21000 \(m^2/kg\). The retain percentage of fly ash in the 45 \(\mu m\) sieve was 28.99%. The added chemical admixture was only superplasticizer (Sika ViscoCrete-5930). In this work, three plate samples with dimension of 200x200x50 mm were cast. For each mixture, one plate was prepared to conduct the abrasion resistance test. To conduct the repeated impact test, twelve disk specimens were cast. To direct the compressive strength test, 18 cubes were prepared, six for each mixture.

**Table 1.** Fiber combinations of the three RPC mixtures SF6, SF15 and SF6-15

| Mix Designation | SF6 \(^a\) (6 mm) | SF15 \(^b\) (15 mm) |
|-----------------|-------------------|---------------------|
| S6              | 2.5               | 0                   |
| S15             | 0                 | 2.5                 |
| S6-15           | 1.25              | 1.25                |

\(^a\) 6 mm length micro-steel fiber.  
\(^b\) S15 - 15 mm length micro-steel fiber

**Table 2.** Properties of the used micro-steel.

| Property                  | SF6       | SF15      |
|---------------------------|-----------|-----------|
| Density (kg/m\(^3\))      | 7800      | 7800      |
| Fiber Length (mm)         | 6         | 15        |
| Fiber Diameter (mm)       | 0.12      | 0.2       |
| Aspect Ratio              | 50        | 75        |
| Ultimate Tensile Strength (MPa) | 2850  | 2600     |

**Table 3.** Mix proportions of the mixtures SF6, S15 and SF6-15

| Cement (kg/m\(^3\)) | Fly Ash (kg/m\(^3\)) | Silica Fume (kg/m\(^3\)) | Silica Sand (kg/m\(^3\)) | Water (kg/m\(^3\)) | SP (kg/m\(^3\)) | W/CM | Fiber (Vf %) |
|----------------------|----------------------|--------------------------|--------------------------|-------------------|----------------|------|--------------|
| 800                  | 120                  | 240                      | 960                      | 232               | 47             | 0.2  | 2.5          |

**Table 4.** Properties of the used cement

| Properties              | Results |
|-------------------------|---------|
| SiO\(_2\) (%)           | 21.04   |
| FeO\(_2\) (%)           | 5.46    |
| Al\(_2\)O\(_3\) (%)     | 2.98    |
| CaO (%)                 | 63.56   |
| MgO (%)                 | 2.52    |
| SO\(_3\) (%)            | 2.01    |
| f-CaO (%)               | 0.76    |
| Loss on ignition (%)    | 1.38    |
| Specific surface (m\(^2\)/kg) | 362   |
| Specific gravity        | 3.15    |
| Fineness (% retain in 45 \(\mu m\)) | -     |

3. Results and Discussion
It was observed that the compressive strength of the hybrid mixture FS6-15 recorded the highest value of compressive strength among the three mixtures at both ages of seven and 28 days. Its compressive strength was 58.7 and 82.8 MPa at the two ages, respectively, while the specimens of SF15 recorded the lowest compressive strength among the tested groups at seven and 28 days. Its compressive strength was 48.7 and 77.7 MPa for the ages of seven and 28 days, respectively. The result of SF6 was quite close to the result of SF6-15, However, limited differences were observed among all mixtures,
hence, it still not assured that one of the mixtures can be considered as the best regarding the compressive strength.

According to experimental work results, the specimen of SF6 with 2.5% of 6 mm length micro-steel fiber showed impact energy higher than the impact energy of the hybrid steel fiber sample (SF6-15), but the difference between these two specimens was slight. On the other hand, the specimen with 2.5% of 15 mm length micro-steel fiber (SF15) showed the highest impact energy of 7.03 KJ, its impact energy was approximately twice that of SF6 and SF6-15, which were 3.64 and 3.21 KJ, Respectively, as shown in Figures 3 to 8.

Figure 3 shows that the percentage abrasion weight loss of group SF6-15 at the first two hours was higher than the percentage abrasion weight loss of group SF6, while that of SF15 showed the lowest percentage among all groups of specimens. After four hours of the abrasion test, it can be noticed clearly that the abrasion loss of group SF6 and SF6-15 were approximately the same, nevertheless, the abrasion damage of SF15 was the lowest, as shown in Figure 4.

As presented in Figure 5, the abrasion resistant of SF6 became higher than that of SF6-15 after six hours comparing with the results of the first four hours. At the eighth hour, the abrasion resistant of SF6 decreased to be lower than that of SF6-15 and that trend continued during the last four hours, but the difference between SF6 and SF6-15 increased at the 12th hour, as shown in Figures 4 to 8, while the specimen of SF15 exhibited the highest abrasion resistant along the time of the abrasion test.

The comparison between the impact and abrasion resistance results explained that the sample of SF6-15 showed the highest abrasion resistance during all stages of the abrasion test. For the first six hours, both of the impact and abrasion resistances of SF6 were higher than those of SF6-15. This behavior reversed during the last six hours of the test, the abrasion resistance of SF6 was less than that of SF6-15. The reason of that was specimen of SF6-15 exhibited the average performance of SF6 and SF15. However, the specimens of SF15 showed the lowest percentage abrasion weight loss and the highest abrasion energy, as shown in Figure 9.
4. Conclusions
According to results of the directed experimental program presented in this article, it can be concluded that the abrasion resistance of the mixture SF15 was the highest comparing with the others at each step of the test. Furthermore, its impact resistance was also the greatest. The impact and abrasion resistances increased with the increasing length of the used fiber. The resulted abrasion and impact resistance for SF15 were higher than those of SF6. The test results also revealed that the abrasion resistance of SF6 was greater than the abrasion resistance of SF6-15 during the first six hours. However, in the last six hours, SF6-15 showed abrasion resistance higher than SF6. Thus, it was concluded that the behavior of these samples under the water abrasion and drop-mass impact loads were the same after the first six hours.

5. References
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