The evaluation of the abrasion damage in hydraulic structures using the modified test method

Mostafa H. Hamedi 1, Ali N. Hilo1, Thaar S. Al-Ghasham 1,*, Nadheer S. Ayoob1, Hamid Shirazi2 and Russul N. Al-Mousawy2

1 Department of Civil Engineering, College of Engineering, Wasit University, Iraq.
2 Department of Civil Engineering, College of Engineering, Azad University of Mashhad, Iran.
* Corresponding author: thaar@uowasit.edu.

Abstract. Disastrous damages can occur in the strategic structures such as the stilling basins due to the action of waterborne solid that withdrawn by the flowing water of very high velocities. Such phenomenon can impose high maintenance efforts and costs, and minimize the service life of these structures. One of the available solutions is the improvement of the concrete mixture to resist the abrasion damage. In this paper, the abrasion resistance of normally vibrated concrete mixtures was estimated using a modified abrasion device. Accordingly, 18 specimens were cast. Three various compressive strengths (25, 35, and 55 MPa) were tested at the 7-day and 28-day ages. Furthermore, to improve the abrasion damage of the used apparatus, two paddles with angles of 30 and 60° were used in addition to the original paddle of 45°. The results revealed that for the paddle of 60°, the wearing resistance of concrete was lowered by 11.9 and 49.9% because of the enhancement of the strength from 25 to 35 and 55 MPa at the 28-day age, respectively. Additionally, the lowest abrasive ability of the apparatus was achieved by the use of the standard paddle, while the highest can be achieved by the paddle of 60°.

1. Introduction
Strategic structures are designed to be sustainable throughout their long service life. Actually, hydraulic structures, which are at the head of strategic constructions list, are susceptible to intense risks due to the phenomenon of abrasion. It takes place by the effect of the particles that withdrawn by the flowing water of high velocities during the project operation. In the severe cases, abrasion is able to destroy more than thousand cubic meters of hydraulic concrete; therefore, during the design stage, concerns must be focused to reduce or eliminate its future effects in order to avoid the high maintenance costs and the fatal hazards [1-3].

Abrasion damage takes place usually by three essential steps. Firstly, the pre-abrasion peeling stage occurs, the pressure and the velocity of the flowing water are the predominant factors. In the second step, cracks appear in the surface of the hydraulic concrete because of the impact effect of the withdrawn sediments, the size of these particles can be considered the governing factor. Lastly, due to the triple effect of the mechanical characteristics of the hydraulic concrete, the physical properties of the withdrawn particles, and the velocity of the flowing water, the wearing goes on. Progressively, the concrete paste is ruined, this leads
to the plucking of the aggregate. Thus, very small voids are formed. Little by little, the formed voids are increased and the concrete is abraded with depth ranges from centimeters to higher than meter [1-5]. Due to several previous studies, the abrasion damage is governed by many factors including the hydrostatic pressure and the velocity of the water, the concrete grade and curing, the inclusion of the cementitious additives and the different types of fibers, and the angle of impingement of the particles [5-9].

To estimate the abrasion resistance of the hydraulic concrete, several test apparatuses were adopted around the world. Among these apparatus, the underwater test method can be considered the most widespread device [10]. Its major defect is the use of the chromium steel balls to simulate the actual waterborne sediments. Thus, for more realistic simulation, Messa et al. [11] prepared an abrasion test apparatus that depends mainly on the concept of the underwater test apparatus with several modifications as a specific amount of the sand was used instead of the steel balls of different sizes.

As the modified test apparatus is relatively new, one can observe that there is an actual shortage in the previous experimental studies that depend on this apparatus to evaluate the abrasive resistance of concrete. Thus, the current work aimed to fill this knowledge gap. The effect of the concrete grade and age were investigated. Eighteen samples of different compressive strengths of 25, 35 and 55 MPa were prepared, cured and tested at two various maturing ages of 7 and 28 days. Moreover, two additional paddles with various angles (30° and 60°) in addition to the standard paddle of 45° angle were used to estimate the difference in the abrasive efficiency of the device.

2. Experimental work

2.1 The testing apparatus and the prepared samples

In the current study, the modified abrasion test apparatus, which was suggested by Messa et al. [11] and manufactured for this study as shown in Figure 1, was used to investigate the wearing resistance of the hydraulic concrete. Samples of various concrete grades were prepared. They were cylindrical with a diameter of 350 mm and height of 50 mm. A specific quantity of silica sand of 950 g must be added to the water, which is inside the tank of the device and immerses the concrete sample. The sand in this test method compensated the steel balls of various diameters in the underwater method to provide a realistic simulation for the real waterborne solids. The resulted blend is agitated by agitation paddle with a rotational velocity of 600 rpm by an electrical motor. The standard full testing period is 24 hrs, it must be divided into four steps of six hours. At the end of each interval, the tested sample must be well dried and its dry weight must be recorded. The decrement in its weight represents the abrasion damage.

Concrete mixtures of three different grades of 25, 35 and 55 MPa were cast and tested at two various maturing ages of 7-day and 28-day ages. As aforementioned, two additional paddles were fabricated with angles of 30° and 60° and used as well as the original paddle of 45°. Thus, the total prepared samples were 18 cylindrical specimens. To determine the concrete grade, standard cubes of 150 mm were tested for each mixture.
2.2. The used materials

In this study, as shown in Table 1, different amounts of type R42.5 ordinary Portland cement were used to cast the required samples of various grades. The used coarse and the fine aggregate were locally produced gravel and sand, respectively. Superplasticizer of SP200 with a quantity of 14 kg/m³, which represents 2% of the total water weight, was added to the mixture of the highest grade to obtain the required compressive strength. The cast sample was demolded after one day and was placed inside a temperature-controlled water tank to be cured till the required age for the test.

Table 1. The quantities of mixed materials.

| Material     | Mix Name | G25   | G35   | G55   |
|--------------|----------|-------|-------|-------|
| Cement       |          | 382   | 467   | 700   |
| Coarse aggregate |        | 819   | 819   | 819   |
| Fine aggregate |         | 939   | 854   | 621   |
| Water        |          | 210   | 210   | 196   |
| Water to cement ratio |  | 0.55  | 0.45  | 0.28  |
| SP200        |          | 0     | 0     | 14    |

3. Experimental results and discussion

All the tests results are displayed in this section in the term of percentage weight loss (PWL). It represents the difference between the initial mass of a tested sample and its mass after a specific testing interval divided by its initial mass. PWL can be determined by the following equation:

\[
PWL (%) = 100 \times \frac{(W_i - W_t)}{W_i}
\]

where \(W_i\) is the initial weight of the spacers and \(W_t\) is the weight after a specific testing interval for the same specimen.
3.1 Effect of concrete grade
At the maturing age of 7 days, Figures (2 to 4) show the PWLs of the samples of three various grades that were abraded by the paddles of three different angles 30, 45 and 60°, respectively. One can observe that throughout the test and regardless of the used paddle angles, the PWL lowered highly as the concrete grade enhanced. Absolutely, this can be considered a predictable manner according to the strength development of the concrete surface by the use of concrete with higher grades [1-3]. For all concrete grades, the highest PWLs were recorded for the paddle angle of 60°. For this angle, the improvement of the compressive strength from 25 to 35 MPa by approximately 16%, while it enhanced by 31.5% for the sample of 55 MPa.

![Figure 2](image2.png)

**Figure 2.** The PWLs of various compressive strengths at the age of 7 days and paddle angle of 30°.

![Figure 3](image3.png)

**Figure 3.** The PWLs of various compressive strengths at the age of 7 days and paddle angles of 45°.

![Figure 4](image4.png)

**Figure 4.** The PWLs of various compressive strengths at the age of 7 days and paddle angle of 60°.
In the same way, the PWLs of the same samples at the 28-day age are presented in Figures (5 to 7). For all types of the used paddles, the PWLs of the sample of the highest compressive strength were the lowest throughout the test. For example, for paddle of 60°, the final PWLs of the specimens of 25, 35 and 55 MPa were 0.705, 0.567 and 0.432%, respectively. Thus, the abrasive resistance of concrete was increased by 38.7% due to the increment of the compressive strength from 25 to 55 MPa.

In this study, the prepared samples were tested at two various maturing ages, which are 7-day and 28-day. The effect of maturing age for the various compressive strengths tested by the paddle of 30° is shown in Figures (8 to 10). Basically, as the concrete age increases the abrasion damage for the concrete surface reduces significantly.

3.2 Effect of maturing age
In this study, the prepared samples were tested at two various maturing ages, which are 7-day and 28-day. The effect of maturing age for the various compressive strengths tested by the paddle of 30° is shown in Figures (8 to 10). Basically, as the concrete age increases the abrasion damage for the concrete surface reduces significantly.
For the same paddle angle, for specimens of 25, 35, and 55 MPa, the wearing damage was reduced by 17.4, 17.9 and 24.5%, respectively, due to maturing of concrete from 7-day to 28-day age. For the sample of 25 MPa, the final PWLs were 0.726 and 0.6%, while for the sample of 55 MPa were 0.452 and 0.341%, respectively.

Figure 8. The PWLs of various maturing ages for the specimen of 25 MPa abraded by the paddle of 30°.

Figure 9. The PWLs of various maturing ages for the specimen of 35 MPa abraded by the paddle of 30°.

Figure 10. The PWLs of various maturing ages for the specimen of 55 MPa abraded by the paddle of 30°.

The PWLs of both maturing ages for the three different compressive strengths of 24, 35, and 55 MPa that abraded by the paddle of the angle of 45° are displayed in Figures (11 to 13). The final abrasion resistance increment due to the age development from 7 to 28 days for the sample of 25 MPa was 30%, while it was 38% for the sample of 55 MPa.
Figure 11. The PWLs of various maturing ages for the specimen of 25 MPa abraded by the paddle of 45°.

Figure 12. The PWLs of various maturing ages for the specimen of 35 MPa abraded by the paddle of 45°.

Figure 13. The PWLs of various maturing ages for the specimen of 55 MPa abraded by the paddle of 45°.

In the same way, Figures (14 to 16) show the obtained results for the paddle of 60°. The occurred development in the abrasion resistance for the sample of 25 MPa due to the age development from 7 to 28 days was 14%. The improvement percentages for the samples of 35 and 55 MPa were 17.8 and 23%, respectively. Thus, the paddle of 45° gives the highest differentiation between the maturing ages, while the remaining used angles provide approximately the same.
According to the previously shown experimental results, it can be proven that the first week of the concrete age supplies the highest portion of the final wearing resistance that can be acquired from the beginning of the hardening time to the end of the first 28 days. Thus, in several emergency cases, such as for the maintenance, the concrete of the appropriate properties can be depended to resist the abrasion damage at the age of seven days.

3.3 Effect of the angle of the agitation paddle

According to the previously shown experimental results, it can be proven that the first week of the concrete age supplies the highest portion of the final wearing resistance that can be acquired from the beginning of the hardening time to the end of the first 28 days. Thus, in several emergency cases, such as for the maintenance, the concrete of the appropriate properties can be depended to resist the abrasion damage at the age of seven days.

3.3 Effect of the angle of the agitation paddle

To determine the influence of the paddle angle on the wearing efficiency of the used test apparatus, two angles of 30° and 60° were applied in addition to the original paddle of 45°.

Figure 14. The PWLs of various maturing ages for the specimen of 25 MPa abraded by the paddle of 60°.

Figure 15. The PWLs of various maturing ages for the specimen of 35 MPa abraded by the paddle of 60°.

Figure 16. The PWLs of various maturing ages for the specimen of 55 MPa abraded by the paddle of 60°.
Figures (17 to 19) display the influence at the maturing age of seven days for the tested samples of the various compressive strengths. The obtained results revealed that the paddle of 45° exhibited the minimum abrasion damage, while that of 60° showed the highest. For the sample of 25 MPa, the final PWLs were 0.6, 0.725 and 0.82% for angles of 45°, 30° and 60°, respectively. On the other hand, they were 0.341, 0.452 and 0.562% for the sample of the highest compressive strength in the same sequence.

Figure 17. The PWLs of various angles for the sample of 25 MPa at the 7-day age.

Figure 18. The PWLs of various angles for the sample of 35 MPa at the 7-day age.

Figure 19. The PWLs of various angles for the sample of 55 MPa at the 7-day age.

The effect of the used angle of the paddle for the tested samples of the various compressive strengths is showed in Figures (20 to 22). For the sample of the lowest compressive strength, the use of the paddles of
30 and 60° instead of the original one increased the abrasion ability of the test apparatus by 42.5 and 67.5%, respectively. On the other hand, in the same sequence, that increments were 61.6 and 101.4% for the sample of the highest compressive strength. Thus, one can notice that as the compressive strength increases, the influence of the angle magnifies considerably.

![Figure 20](image1.png)

**Figure 20.** The PWLs of various angles for the sample of 25 MPa at the 28-day age.

![Figure 21](image2.png)

**Figure 21.** The PWLs of various angles for the sample of 35 MPa at the 28-day age.

![Figure 22](image3.png)

**Figure 22.** The PWLs of various angles for the sample of 55 MPa at the 28-day age.

According to the obtained experimental results, the paddle of the angle of 60° caused the highest abrasion damage for the surfaces of the various specimens of various strengths regardless of their maturing age; therefore, it is highly recommended to be used to test the abrasion resistance of the hydraulic concrete due
to its great ability to differentiate the potential resistances of the various samples, especially the samples of the high strength concrete HSC. Figure (23) depicts the effect of the paddle angle on the tested sample.

Figure 23. The effect of the paddle angle.

4. Conclusions
Due to the obtained experimental results that discussed previously, the following points summarize the main conclusions of this study:

1. The percentage weight loss (PWL) reduced significantly due to the enhancement of the compressive strength of the hydraulic concrete regardless the maturing age and the angle of the used paddle. As an example, for the maturing age of 28 days, the reduction in the abrasion damage was in the range of 38.7 to 105% because of the enhancement of the strength from 25 to 55 MPa for the various angles of the paddle.

2. For these types of concrete mixtures that were studied in this work, the average of the acquired abrasion resistance of the concrete during the maturing age of 7 days represented approximately 78.5% of the entire gained resistance during the first 28 days. Thus, a hydraulic concrete with appropriate properties can be subjected to the effect of the abrasive particles at the cases of emergency at the age of 7 days.

3. For the different strengths and at the various maturing ages, the highest abrasion action was achieved due to the use of the agitation paddle of 60°, while the standard paddle of 45° caused the lowest. On average, the use of the paddle of 30 and 60° instead of the standard paddle increased the abrasion damage by 43.9 and 75% at the 28-day age, respectively. Consequently, the paddles of 30 or 60° can be used instead of the standard paddle to achieve a wide differentiation in the wearing loss for the specimens of the convergent characteristics and the high strength concrete specimens. Moreover, it may minimize the required time for the test.

5. References
[1] ACI Committee 210 2003 Erosion of concrete in hydraulic structure (ACI 210R-03) American concrete institute, USA 1–24.
[2] Abid S R, Hilo A N, Ayoob N S and Daek Y H 2019 Underwater abrasion of steel fiber-reinforced self-compacting concrete Case Studies in Construction Materials 11 1–17.
[3] Ayoob N S and Abid S R 2020 Analysis of the abrasion rates in concrete surfaces of hydraulic structures IOP Conf. Series: Material Science and Engineering 888 1–9.
[4] Liu Y W, Yen T and Hsu T H 2006 Abrasion erosion of concrete by water-borne sand Cement and Concrete Research 36 1814–1820.
[5] Abid S, Hilo A and Daek Y. 2018 Experimental tests on the underwater abrasion of engineered cementitious composites Construction and Building Materials 171 779–792.
[6] Horszczaruk E 2012 Abrasion resistance of high-performance hydraulic concrete with polypropylene fibers Tribologia 1 63–72.

[7] Liu Y W, Cho S W and Hsu T H 2012 Impact abrasion of hydraulic structures concrete Journal of Marine Science and Technology 20 253–258.

[8] Turk K and Karatas M 2011 Abrasion resistance and mechanical properties of self-compacting concrete with different dosages of Fly ash/silica fume Indian Journal of Engineering and Materials Science 18 49–60.

[9] Ayoob N S, Abid S R, Hilo A N and Daek H Y 2020 Water-impact abrasion of self-compacting concrete Magazine of civil engineering 96(4) 60–69.

[10] ASTM C1138-97 1997 Standard test method for abrasion resistance of concrete (Underwater Method) ASTM International, West Conshohocken, USA 1–4.

[11] Messa G V, Branco R D, Filho J G D and Malavasi S A 2018 Combined CFD-experimental method for abrasive erosion testing of concrete J. Hydrol. Hydromech 1 (2018) 240–246.