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# Experimental study on erosion depth in hydraulic structures

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ABSTRACT

In many hydraulic constructions, such as dams, spillways, and stilling basins, large quantities of concrete can be ruined because of the long-term action of water-borne solids. To a great extent, for hydraulic structures, the durability relies on the resistance that the concrete surface performs against the mechanical wear. The surface damage caused by the uninterrupted material removal process, which induced by the impact of the water-borne solid particles, is termed hydro-abrasion. In nearly all hydraulic structures, this kind of progressive deterioration of the concrete surfaces is observed with different intensities. Obviously, such hydro-abrasive concrete wearing normally results in a reduction in the service life of the hydro-technical facility, and consequently because of the required repairs, the non-functioning of the facility during the repair period results in an expenditure increment. The rate of concrete erosion was tested by the original equipment manufactured in the Construction Laboratory of Civil Engineering department / Wasit University, by directing a high velocity jet of a mixture of water and sand, striking the concrete plates. To satisfy the research requirements, 24 samples of concrete were prepared and categorized into three mixtures with compressive strengths of 25, 35, and 45 MPa, they were tested after 7 days of maturing. Further, the effect of the impingement angle was also determined. Experimental estimations was made of the four different angles (0, 30, 45, and 60°) with the horizon. From the findings of the experimental investigations, it was clear that the maximum erosion depth can be reached when the flow inclination angle was 45°, while the lowest rate can be achieved by the flow inclination angle of 60° with horizon.


## 1. Introduction

Concrete is the most popular material in the construction of hydraulic structures; therefore, abrasion erosion looms large as one of the principal problems confronts these structures during their operation. In fact, the loads resulting from the transportation of the water borne sediments lead the cement mortar to decompose. This problem acquires major significance under the conditions of high velocities of water flow [1–4]. Thus, concrete abrasion is one of the main problems that hydraulic structures face. Water flow is responsible for the conveyance of huge quantities of sand and gravel and other debris. These solid water-borne particles are moved either rotationally, transnationally, or as a combination of these movements, based on the condition of the water flow at that point, and the hydro technical processes that occur within it. The impact of solid particles on the contact surface with the water induces cracks to form. The material will then break-up and its internal connection will be damaged [5–7]. From a previous numerical study performed on a Type III stilling basin employing flow-3D software, it was evident that the abrasion highly affected the chute block surfaces and the baffle piers because of the higher velocities and intense pressures [8]. The abrasion loss was observed to substantially decline as the concrete grade was increased [2–4,9]. Further, when fibers were included in the concrete, the abrasion resistance was noted to rise [10–13]. From recent studies, the real paucity of researches, which focused on assessing the erosion rate using this significant and modern method of testing, is really obvious. Thus, in this study, a series of experiments were done to determine the degree of the flow inclination angle that highly influences the damage of the concrete surface due to the abrasion phenomenon, and also to calculate the erosion depth by using a new tool elcometer 224.

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## 2. Experimental work

### 2.1. Test procedure and studied samples

The experimental tests to estimate the abrasive resistance of concrete were carried out using the water jet test device that past fabricated in the Hydraulic Laboratory of Engineering College/ Wasit University, Iraq. Fig. 1 shows the details of the used device.

The abrasion test specimen was a plate with the specified dimensions of 200 × 200 × 50 mm. The sample was fixed inside the specimen holder of the device, which is adjustable to fulfill all the applied four angles of flow inclination (0, 30, 45, and 60°), the distance between the jet and the specimen is 20 cm [6].

The most popular testing procedure, the water jet flow, was used to identify the relative abrasion resistance of the concrete surface caused by the impact of the water flow of various angles and the water borne particles. It was Liu et al., who first proposed this method, in Taiwan [6,14,15]. In their study, mixture of sand and water was used to induce the abrasion damage. The produced mixture simulates the abrasive materials acting against the hydraulic structures in a real-life scenario. Sand with a particle size of 0.6 mm was mixed with the water. The concentration of the sand in the produced mixture was 30 kg/m$^3$. The water tank base had the dimensions of 2.0 × 0.75 m, while the tank height was 1.5 m. The tank was filled with 1 m$^3$ of water. To ensure that the water and sand were homogeneously mixed, two electrical mixers were placed inside the tank. A centrifugal pump was attached to draw the mixed water via an intake pipe. The mixed was pumped directly through a specific rectangular nozzle with dimensions of 200 × 10 mm, at a velocity of 10 m/s, on the upper surface of the concrete plate, as shown in Fig. 1.

The total testing time took three hours to complete. An elcometer, one of the new tools to determine the erosion rate, was used to assess the depth of the erosion, as shown in Fig. 2. The experimental work involved the preparation and casting of 24 plates of normal concrete mixtures, having three distinct compressive strengths (25, 35, and 45 MPa) and tested by the four various angles. The average of two samples was determined and considered the abrasion damage of this mixture tested by that specific angle. After 24 h, they were demolded and cured inside a specific water tank with the temperature of 23 °C, until the required concrete age was reached. The concrete age that depended in this study was seven days. For compressive strength test, the average of three cubic samples, with edge length of 150 mm, was recorded and calculated for each of the three mixtures. All tests were carried out at the age of seven days.

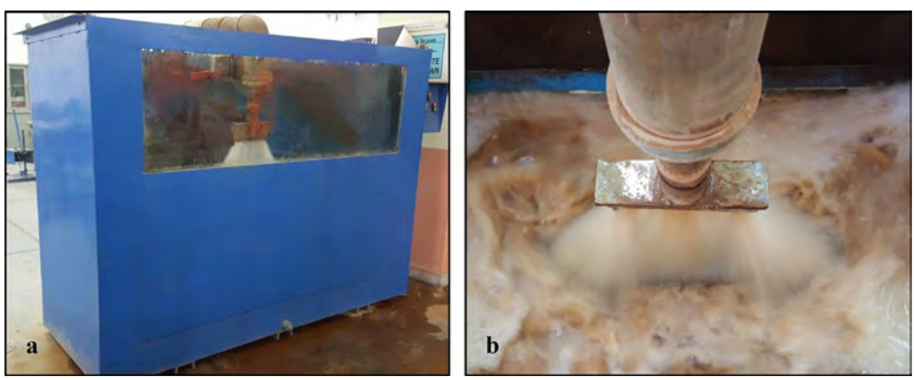


**Fig. 1.** (a) Water –Jet test Machine; (b) Jet.


**Fig. 2.** (a) Elcometer 224; (b) Elcometer needle.

**Table 1**
Proportions of the materials utilized.

| Material | Mixture | | |
|---|---|---|---|
| | C25 | C35 | C45 |
| | Quantities kg/m$^3$ | | |
| Cement | 339 | 438 | 553 |
| Sand | 894 | 894 | 810 |
| Gravel | 992 | 992 | 992 |
| Water | 210 | 210 | 210 |
| Water to cement ratio | 0.62 | 0.48 | 0.38 |

### *2.2. Materials and mixture proportions*

In this study, specific quantities of type R42.5 ordinary Portland cement were used to prepare the concrete samples of different compressive strengths. Locally produced sand and gravel with maximum size of 10 mm were used as fine and coarse aggregates, respectively. Table 1 shows the quantities of the used materials.

## 3. Elcometer

The elcometer 224, as shown in Fig. 2, was used to assess the depth of erosion of the concrete plates. It is an easy to use depth gauge. The gauge must be firstly adjusted to read zero on a glass for calibration purposes, then it must be placed above the sample surface and a spring mounted needle measures the profile of depths. Keeping the surface profile needle perpendicular over each test sample, five readings were taken over a 150 mm$^2$ surface area [16]. From the average of these readings, the surface profile peak was identified. As stated, this study included 24 concrete specimens, with three different compressive strengths (25, 35, 45 MPa) and four flow angles (0, 30, 45, and 60°).

The specimens were divided into small areas (150 mm$^2$) according to elcometer guidelines [16]. Then 19 points were selected for each specimen, as shown in Fig. 3. Five readings were then taken for each point as shown in Fig. 4. The average of these five readings was calculated. These indicated the depth of the erosion damage (in mm). As aforementioned, the abrasion test took three hours to be completed. Using all these points, the average

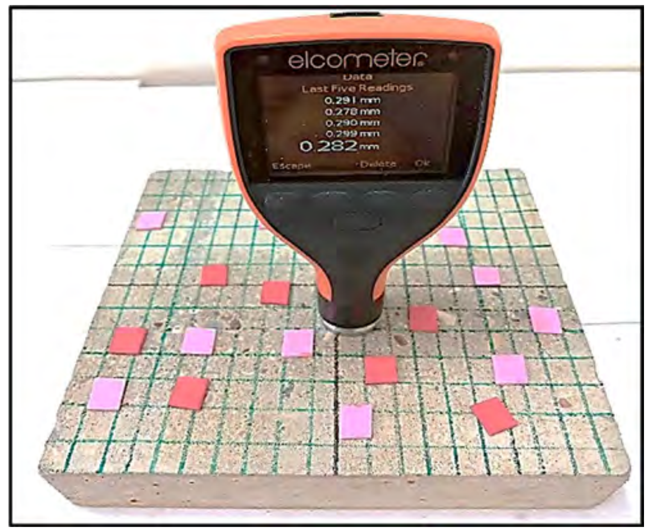


**Fig. 4.** Elcometer readings.

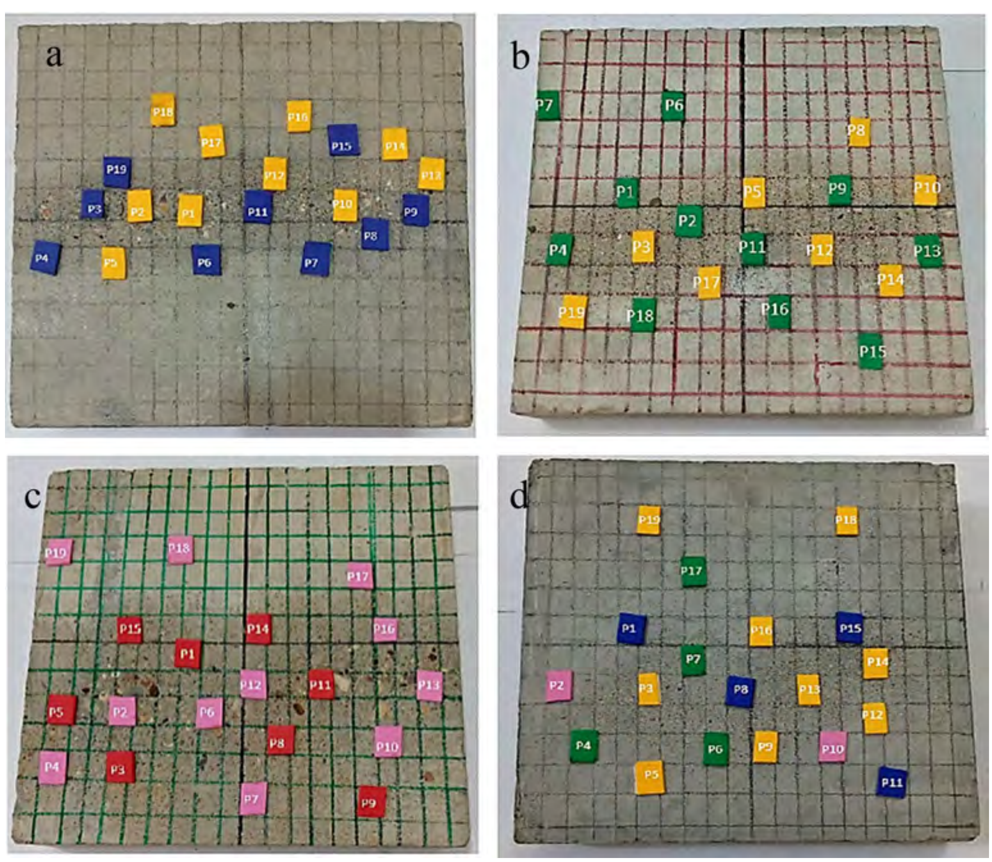


**Fig. 3.** Angle of (a) 0; (b) 30; (c) 45; (d) 60°.

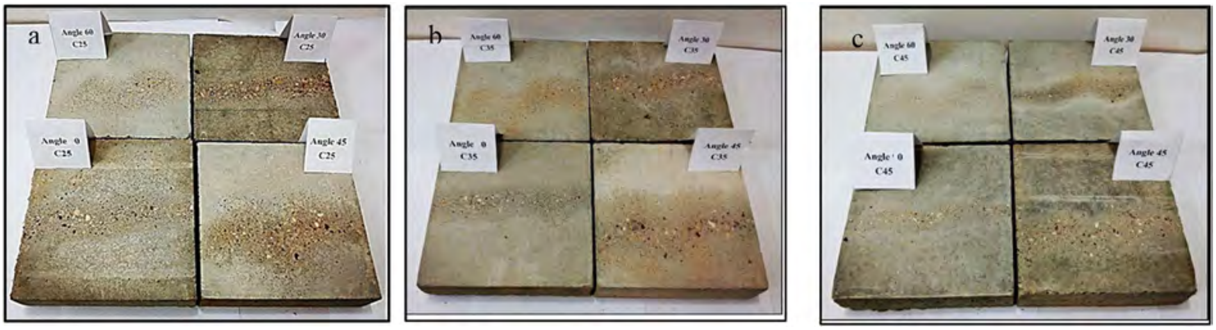


**Fig. 5.** (a) Concrete specimen C25; (b) Concrete specimen C35; (c) Concrete specimen C45.

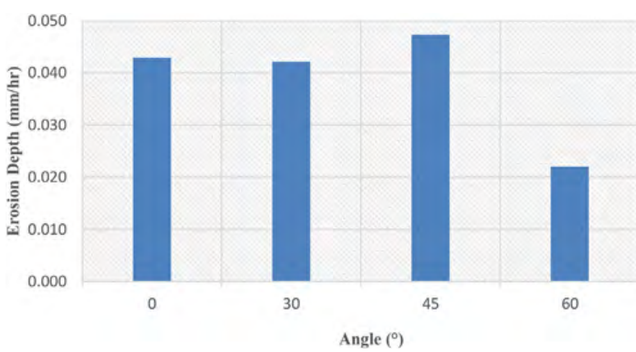


**Fig. 6.** Erosion depth for different angles C45.

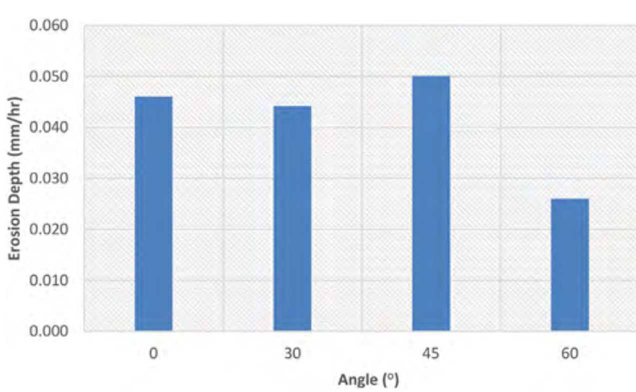


**Fig. 7.** Erosion depth for different angles C35.

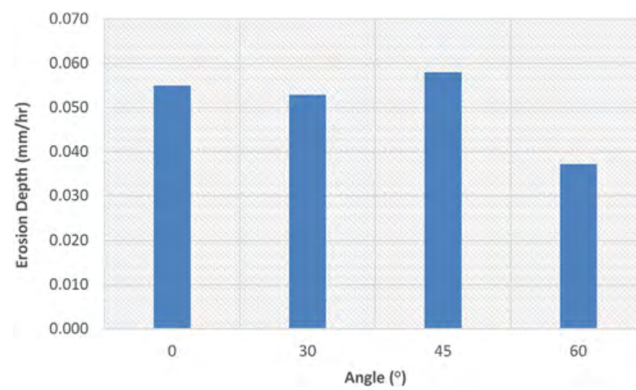


**Fig. 8.** Erosion depth for different angles C25.

of all the readings was taken. These represent the average depth of erosion, for each specimen.

## 4. Results and discussion

Essentially, the effect of the flow inclination angle was examined experimentally using the water jet test method. The effect of the different inclination angles on the rate of the erosion at the surface of each sample tested was shown in Fig. 5. It is evident that the maximum erosion occurred by the flow inclination angle of 45°, whereas the minimum erosion was recorded at the 60° angle with the horizon. Furthermore, the attained experimental results were shown as the depth of the erosion rate. After a specified test interval of a certain compressive strength and a specific concrete age and a flow inclination angle.

### *4.1. Effect of flow inclination angle*

In this study, four flow inclination angles of 0, 30, 45, and 60° with the horizon were examined. All tests were conducted at the concrete age of seven days. In Fig. 5. The effect of the inclination angle was shown using the specimens. It was indicates that the inclination angle of the specimens directly influenced the depth of the erosion. It was obvious that the flow inclination angle of 45° reveals the maximum erosion damage. This occurred because in the case of the perpendicular water jet (0°), the entire pressure was caused by the impact of the water as it strikes the surface. However, in the case of inclined surfaces, the pressure is analyzed as two elements, where only the normal exerted a significant effect on the surface.

On closer examination, the results revealed that the water jet was most effectual on the cross-sectional surface of the 45° specimen and caused intensive abrasion of that surface, which increased the depth of the abrasion damage. Figs. 6–8 as well as Tables 2 and 3 show the erosion depth for different concrete grades and inclination flow angles.

### *4.2. Effect of compressive strength*

Fig. 9 shows the erosion depth of the samples of different compressive strengths of 25, 35, and 45 MPa during the test when the flow inclination angle was held at 0, 30, 45, and 60° with the horizon.

It was clearly evident that at all the four used angles, the erosion depth significantly decreased as the compressive strength increased. This, certainly, is a predictable behavior due to the enhancement of the concrete surface, as well as the increase in the compressive strength. This finding completely compatible with

**Table 2**
Erosion depth for inclination flow angles (0 and 30$^0$) with different grads.

| Inclination angles | 0° | | | 30° | | |
|---|---|---|---|---|---|---|
| Grads | C25 | C35 | C45 | C25 | C35 | C45 |
| Erosion depth mm/hr | 0.096 | 0.083 | 0.081 | 0.095 | 0.082 | 0.08 |
| | 0.089 | 0.081 | 0.072 | 0.087 | 0.08 | 0.078 |
| | 0.086 | 0.076 | 0.07 | 0.083 | 0.077 | 0.075 |
| | 0.08 | 0.067 | 0.065 | 0.075 | 0.068 | 0.065 |
| | 0.077 | 0.061 | 0.058 | 0.072 | 0.063 | 0.059 |
| | 0.076 | 0.059 | 0.056 | 0.07 | 0.057 | 0.048 |
| | 0.074 | 0.056 | 0.055 | 0.068 | 0.05 | 0.046 |
| | 0.068 | 0.053 | 0.052 | 0.065 | 0.048 | 0.047 |
| | 0.066 | 0.051 | 0.049 | 0.06 | 0.047 | 0.045 |
| | 0.05 | 0.042 | 0.04 | 0.055 | 0.042 | 0.041 |
| | 0.048 | 0.038 | 0.035 | 0.05 | 0.048 | 0.046 |
| | 0.044 | 0.035 | 0.028 | 0.045 | 0.043 | 0.042 |
| | 0.037 | 0.035 | 0.03 | 0.044 | 0.028 | 0.027 |
| | 0.035 | 0.033 | 0.027 | 0.033 | 0.022 | 0.021 |
| | 0.03 | 0.029 | 0.026 | 0.027 | 0.018 | 0.017 |
| | 0.029 | 0.025 | 0.024 | 0.024 | 0.023 | 0.022 |
| | 0.025 | 0.02 | 0.022 | 0.016 | 0.011 | 0.01 |
| | 0.02 | 0.018 | 0.014 | 0.02 | 0.018 | 0.016 |
| | 0.015 | 0.013 | 0.011 | 0.016 | 0.015 | 0.014 |

**Table 3**
Erosion depth for inclination flow angles (45 and 60$^0$) with different grads.

| Inclination angles | 45° | | | 60° | | |
|---|---|---|---|---|---|---|
| Grade | C25 | C35 | C45 | C25 | C35 | C45 |
| Erosion depth mm/hr | 0.1 | 0.093 | 0.092 | 0.075 | 0.07 | 0.055 |
| | 0.096 | 0.085 | 0.083 | 0.065 | 0.065 | 0.048 |
| | 0.085 | 0.08 | 0.08 | 0.063 | 0.03 | 0.03 |
| | 0.083 | 0.08 | 0.078 | 0.055 | 0.025 | 0.022 |
| | 0.082 | 0.079 | 0.075 | 0.052 | 0.022 | 0.021 |
| | 0.078 | 0.077 | 0.071 | 0.05 | 0.02 | 0.019 |
| | 0.076 | 0.066 | 0.063 | 0.046 | 0.025 | 0.023 |
| | 0.07 | 0.058 | 0.055 | 0.04 | 0.032 | 0.026 |
| | 0.063 | 0.055 | 0.05 | 0.034 | 0.019 | 0.018 |
| | 0.058 | 0.05 | 0.045 | 0.031 | 0.019 | 0.016 |
| | 0.054 | 0.048 | 0.044 | 0.029 | 0.022 | 0.02 |
| | 0.05 | 0.045 | 0.04 | 0.025 | 0.018 | 0.021 |
| | 0.048 | 0.029 | 0.026 | 0.026 | 0.019 | 0.019 |
| | 0.044 | 0.023 | 0.022 | 0.02 | 0.022 | 0.016 |
| | 0.04 | 0.022 | 0.02 | 0.029 | 0.022 | 0.02 |
| | 0.03 | 0.02 | 0.016 | 0.015 | 0.016 | 0.011 |
| | 0.018 | 0.015 | 0.014 | 0.02 | 0.02 | 0.015 |
| | 0.015 | 0.014 | 0.012 | 0.016 | 0.012 | 0.01 |
| | 0.012 | 0.011 | 0.01 | 0.016 | 0.016 | 0.008 |

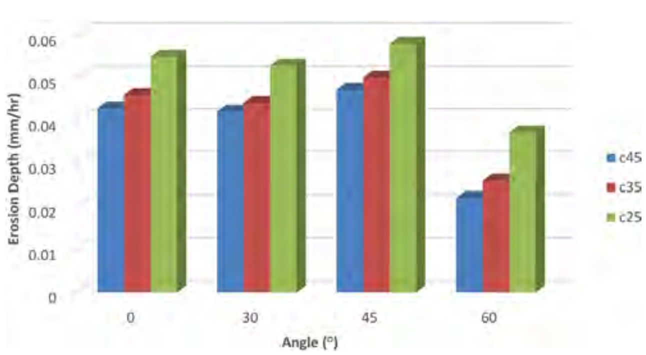


**Fig. 9.** Erosion depth for different compressive strength.

the results reported in the literature [8–9,17]. Evidently, irrespective of the compressive strengths, it was the flow inclination angle of 45° with that showed the maximum abrasion rate. The angle of 60°, on the other hand, produced the lowest rate because less number of sand particles collisions on concrete surface due to the impact of angle so the erosion depth decreased.

## 5. Conclusions

The experimental study was helpful in determining the effect of the flow inclination angle on the rate of erosion of the concrete specimens. These findings will enable the design engineer, maintenance personnel, inspector and operational stuff to project or estimate the erosion depth and the maximum area of destruction under normal and disrupted conditions of operation. The following points represent the main conclusions of this study:

- The maximum depth of the abrasion damage was achieved using the 45° angle with the horizon, while the minimum depth was evident at the 60° angle.
- In fact, a significant increase in the erosion depth was seen in response to the decrease of the compressive strength.
- The elcometer, a new tool, can be depended to measure the depth of the erosion rate and the depth of the erosion at each point exactly. This measuring technique is more precise method to estimate the abrasion damage than calculating the total weight loss that used in the previous experimental studies.

## CRediT authorship contribution statement

**Rawaa H. Ismaeil:** Investigation. **Ali N. Hilo:** Supervision, Data curation, Conceptualization. **Thaar S. Al-Gasham:** Visualization, Methodology, Writing - original draft. **Nadheer S. Ayoob:** Writing - review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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