Erosion of Roller Compacted Concrete exposed to different water conditions

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Abstract – ***Nowadays, due to development of hydraulic structures such as dams, the durability issue of concrete is very important parameter of hydraulic structures. Roller Compacted Concrete (RCC) is new technology gaining popularity in the recent years due to its low cost, rapid construction, and using opportunity of by-products. RCC is widely used in the world for dam's construction.***

The key issue in this regard is the concrete resistance against erosion which is related to water/ cement ratio and the crystalline formation of the particles in concrete.

The experimental program of this study was based on preparing specimens of three mixes of RCC with different water/ cementitious ratio and one mix of conventional concrete. An instrument was manufactured for exposing the specimens to different water pressure, different types of water, different angles of projections and different time intervals.

The total erosion was measured, studied, and analyzed. It was found that the studied parameters were actively affecting the erosion value of the roller compacted concrete.

Keywords**:** (Concrete, Roller Compacted, Erosion, Durability, Hydraulic Structures)

1. INTRODUCTION

The first two large RCC gravity dams in the U.S. Willow Creek in Oregon and Upper Stillwater in Utah were built in the 1980s. These dams experienced seepage through lift joints and at shrinkage cracks. Since that time, design engineers, owners, and contractors have been looking for innovative methods to improve durability and aesthetics of RCC and to limit seepage. Several facing systems are being used on dams built today, including air-entrained conventional concrete with crack inducers and water stops, precast concrete panels, and waterproofing membranes. Five medium sized RCC gravity dams were built in the U.S. between 2004 and 2008. [1]

RCC may be considered for application with no slump concrete that can be transported, placed and compacted using earth-fill construction equipment. Applications of RCC to date have centred on dams instead of concrete gravity and earth-fill dams. It can also be used for pavements to accommodate heavily loaded vehicles traveling at low speeds. These include hardstands for tracked vehicles, truck, and aircraft parking areas. Moreover, RCC may be used for street paving, highways, and parking lots. In addition to that, RCC can be used for emergency repairs and rehabilitation of earth-fill dams. For several dam projects, the use of RCC may result in a more economical layout of project attributes such as an over-the-crest spillway as opposed to a side-channel spillway. [2]

A goal of mass-concrete mixture proportioning, which is also applicable to RCC mixture proportioning, is to provide a maximum content of coarse aggregate and a minimum amount of cement while developing the required plastic and hardened properties at the least overall cost [3]. Optimum RCC proportions consist of a balance between good material properties and acceptable placement methods. This includes minimizing segregation. [4]

Concrete erosion is a major concern and must be considered when designing spillway aprons, stilling basin channels, and other concrete surfaces subjected to high-velocity flows, or when designing concrete surfaces exposed to the action of abrasive materials such as sand, gravel, or other waterborne debris. Erosion damage of concrete surfaces can be caused by cavitation or abrasion. [5]

2. LITERATURE REVIEW:

Many studies have been conducted all over the world to evaluate the effect of different conditions on the rate of erosion of concrete. Different properties of concrete as well as different exposure conditions were viewed. These studies included theoretical and experimental work. Tests to assess the erosion resistance of soil-cement when subjected to either high velocity water or a bed load of water-borne particles go as far back as 1942. Test methods were developed to determine the resistance of soil-cement to forces greater than ordinary wave action or low-velocity flow (less than 10 ft/ sec [3 m/ sec]). In the laboratory, continuously flowing water, water jets, and specially developed test apparatus were used for this purpose. In order to obtain meaningful results

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in a relatively short period of time, the test method in the laboratory had to be either (1) severe, (2) accelerated, or (3) Conducted on specimens whose strength was weaker than that usually specified for actual construction. Most laboratory tests were conducted on the compacted surface of the materials and not the unrestrained or possibly poorly compacted edges of soil-cement or RCC that may also be exposed to flowing water in field applications.

According to Liu (1980) a number of stilling basins and other structures at existing Corps dams had been damaged due to abrasion of concrete caused by turbulent water flow that contained large rock particles and other materials, such as pieces of steel. In order to evaluate the abrasion erosion resistance of various materials considered for repair of these concrete structures, the Corps developed an underwater abrasion erosion test method. An apparatus developed by Liu (1980) was initially used to evaluate (a) Conventional concrete, (b) Fiber-reinforced concrete, and (c) Polymer concrete. The test has been adopted as ASTM C 1138 Standard Method for Abrasion Resistance of Concrete (Underwater Method). [6]

According to Corps (Holland 1983) and (Simons 1992). Tests to determine the abrasion erosion resistance of various concretes subjected to severe wear conditions and for Puget Sound Power and Light. The conclusions and recommendations from the Corps (Holland 1983) and (Simons 1992) studies [7, 8] included:

- Use the hardest available aggregate.
- Use the lowest practical water-cement ratio, which produces the highest practical compressive strength.

Omoregie, Gutschow, and Russell (1994) tested the abrasion erosion of conventional concrete in order to compare the three materials (soil-cement, RCC, and conventional concrete). Four mixes of each material were tested. The results of the test confirmed previous studies of abrasion erosion that wear progression is non-linear. Greater wear occurred earlier in the test than later on, except for the PCC containing 3/ 4-in. (19-mm) maximum size aggregate and the highest cement content (705 lb/ yd3 [418 kg/ m3]). This concrete had a 28-day compressive strength of 7,255 psi (50 MPa). [9]

The U.S. Bureau of Reclamation tested RCC mixtures for the Rio Salado project on the Salt River, through Phoenix. They used the underwater abrasion erosion test (ASTM C 1138) to test the wear of RCC mixtures planned for two flood control projects in the Phoenix, Arizona area. This work was done for the Corps of Engineers' Los Angeles Districts (U.S. Army Corps of Engineers, 1999). For the Rio Salado project, four mixtures were tested: two with Portland cement only and two with cement plus the addition of fly ash. Also, several aggregate gradations up to 1-1/2-in. (38-mm) maximum size aggregate (MSA) were tested including a 3/4-in. (19-mm) maximum size Arizona base course. [10]

They concluded that the abrasion resistance of the RCC specimens increased with increasing strength and maximum size aggregate. In the Rio Salado test program, there were several cases where the lower cement content (lower compressive strength) RCC showed less erosion than a higher strength specimen produced with a greater cement percentage. Because this unanticipated result occurred in both test programs, it provided evidence that aggregate properties are a larger factor in abrasion erosion resistance than compressive strength of RCC. [10]

3. MATERIAL AND TESTS:

3.1 Introduction

In order to implement the experimental work of this research special equipment and materials were needed. According to the literature searched, we did not find any previous research on erosion of concrete that has been done in the Iraqi universities therefore it was needed to start with the requirement of this research almost from zero level. We had to provide the raw materials and to prepare and manufacture the testing system by our private effort.

3.1.1 Materials:

Two different types of concretes are used; Conventional and Roller Compacted Concrete. Cement, aggregate and water were used for the conventional concrete mixes, fly ash was added for all RCC mixes while a super-plasticizer was added to only one mix of the RCC mixes.

3.2.1 Cement

The cement type that used in this study was ordinary Portland cement of type I, manufactured by Mass factory / Sulaymaniyah. The cement used conforms to the Iraqi standard limits No.5, 1984 [11]. It was brought from Mass cement factory and was stored in a dry place till the day of mixing.

3.2.2 Fine Aggregate (sand)

Clean, natural river sand brought from Asky Kalak quarry/ Hawler was used for this work. The grading of the sand was conformed to ASTM C-33 [12].

3.2.3 Coarse Aggregate (Gravel)

Natural river gravel (brought from Asky-Kalak / Hawler quarries) with maximum size 19mm was used in the experimental work. The material was washed then left to be saturated surface dry, then used. The material was sieved to maintain the specified limits for gradation of the ASTM C-33 limits.

3.2.4 Water

In all concrete mixes and for curing purposes, tap water from the city network of Hawler was used which is free from clay

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and organic impurities. The water can be used for drinking purposes.

3.2.5 Admixtures

Admixtures were only added to the Roller Compacted concrete mixes.

3.2.5.1 Chemical admixture (Super-plasticizer)

The super-plasticizer E4 (Sika-ViscoCrete Super E4) was used in this study only in one mix of RCC to obtain more strength by reducing water to cementitious material ratio and improving workability. This plasticizer was added to concrete mix according to the recommendations of the manufacturer, it improves the workability and retards the setting of fresh concrete. (Conforms to ASTM C494-Type F)

3.2.5.2 Mineral admixture Pozzolana material (Fly ash)

The physical and chemical properties of the fly ash used are shown in table -1

Table -1: physical and chemical properties of the fly ash

Tests	Required value	
Humidity %	Maximum 3%	
Heating Loss %	Maximum 10%	0.4 %
SO3 %	Maximum 5%	2.88 %
Free Cao		0.16%
Particle size		(+45 micron): 43.39%
Chloride		0.0106%

3.3 Research methodology

The outline of this study is to prepare samples of RCC with different water cementitious ratios. The specimens were to be tested for compressive strength and for erosion resistance under different exposure conditions. These different exposure conditions were projecting a water jet on the upper face of the specimen as follows:

- By using tab water under different pressures.
- By using water containing fine sand particles (water borne particles) to increase the erosion.
- By using different projection angles between the water jet (tap water and water borne particles) and the face of the specimens.

All these tests were repeated for the conventional concrete specimens to evaluate the differences between the erosion resistance of specimens of different mixes of RCC and the erosion resistance of conventional concrete specimens.

3.4 Instruments

3.4.1 Mixing and molding instruments

The following instruments were used to prepare the required specimens: Concrete pan mixer (0.6m3 capacity), hand buggy, aggregate shaker, stop watch (countdown timer), steel type cylinder molds, 21 pieces (φ15*30 cm), 5mm thick (Fig.1) and a Compacting hummer (According to ASTM C 1435-99) [13] was not available, therefore we bought a similar type then we made few modification on it to be conformed to ASTM standards. The compacting hammer shown in (Fig. 2), have a mass (without tamping plate) of 10 kg. The tamping plate is a circular steel plate attached to a metal shaft, which inserts into the Compacting hammer chuck. The diameter of the tamping plate is 140 mm and has a mass of 3 kg.

Fig.1: Cylindrical Molds (Φ15cm * 30cm)

Fig.2: Modified Vibrating Hammer

3.4.2 Testing apparatus

3.4.2.1-Fresh Concrete Testing Apparatuses

1) Slump test set, for conventional concrete and RCC.

2) Modified Vebe apparatus (reference).

The following modifications were done to the Vebe apparatus to conform to ASTM C1170 specifications that required for checking consistency of zero slump concrete. [14]

- A surcharge load of 50Ib (22.7) kg.
- Changing the transparency plastic plate to steel plate to be able to carry the surcharge load. (Fig. 6)

3.4.2.2- Hardened Concrete Testing Apparatus

1. Universal testing machines (capacity 2000 KN)

2. Electronic balance (Accuracy 0.1 gm, capacity 8kg)

3. Erosion testing Instrument: As shown in (Fig -3 and Fig -4) this instrument is composed of iron water tank 1x1x2 m. On this tank, twelve (four x three) water jets were installed and connected to a water network to take the water from the bottom of the tank by means of a water pump. All the jets were installed vertically and the concrete specimens were fixed below the jets with different angles of projection. Three pressure dial gauges were installed on each lane (each lane has four water nozzles). Each pipe line was provided with releasing valve for pressure adjustment. The angles of the

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face of the specimens were 90º, 60º, 30º, 0º degrees with the vertical axis of the water projection jet (Each three specimens were projected to one of these four angles and the average reading of erosion was taken).

	Roller Compacted Concrete mixes for 0.09m3 (for 1m3)			Conventional Concrete
Mix designation	Mix A	Mix B	Mix C	Mix D
Water (L)	11.34 (126)	10.53 (117)	9.72 (108)	18 (200)
Cement (kg)	12.54 (139.33)	12.54 (139.33)	12.54 (139.33)	29.9 (332.23)
Fly ash (kg)	3.66 (40.67)	3.66 (40.67)	3.66 (40.67)	0
Sand (kg)	67.5 (750)	67.5 (750)	67.5 (750)	78.15 (868.3)
Gravel (kg)	127.7 (1418.8)	127.7 (1418.8)	127.7 (1418.8)	91.8 (1020)
Superplasticizer	0	0	%0.99	0
W/CM	0.70	0.65	0.60	0.60

Fig .3 : Erosion Testing schedule

Fig .4 : Erosion Testing Machine

3.5 Mix proportions of concrete

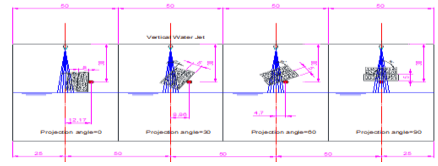
For this study we tried to have practical mixes of roller compacted concrete. The roller compacted concrete mixes proportions were based on targeting 20MPa at 28 days. The conventional concrete mix was also targeting 20 MPa and was

designed according to (ACI 207-5R) method. [15].

Table-2 illustrates the mixes ingredients proportions:

3.6 Specimens Preparation

84 concrete cylinders (Φ15*30) cm were casted. 21 cylinders were casted of each mix. 9 cylinders of each mix were full size and used for compressive strength test (3rd, 7th, 28th day). The other concrete cylinders (12 specimens) were used for the erosion test. The specimens for erosion test were



casted with the same steel cylinders to one third of the cylinder's height.

3.6.3 Fresh concrete testing

3.6.3.1 Slump

After completing mixing process, the fresh concrete was poured into the hand cart, then the fresh concrete was checked for slump, mix(A,B,C) had zero value, except mix D was 82mm, as shown in (Fig. 4 and Fig. 5).

Fig -4 Slump test for RCC **Fig -5** Slump test for Conventional Concrete

3.6.3.2 Consistency test (Vebe time)

After completing mixing operation a sample of fresh concrete about 9 kg was put in Vebe test container (Fig. 6) for checking the consistency time according to the ASTM 1170-91 [14, 16]

3.6.4 Casting & Compacting

Casting was started by placing the concrete mix inside the cylindrical moulds in three layers each compacted by the hummer as described in ASTM C1435 until water appears as a ring around the circle plate within 20 seconds otherwise we have to stop tamping and add the next layer of the mix [13] . Then concrete surface was finished and levelled by steel trowel as shown in Fig.7.

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Fig -6 Modified Vebe apparatus.

Fig -7 Compacting and Casting Specimen

3.7 Curing of concrete

After 24 hours from casting process, the specimens were removed from the moulds as shown in Fig. 8, then the specimens were put in a curing bath that is available in the concrete laboratory for 28 days, according to ASTM C 31 [17], as shown in Fig -9.

Fig-8 After Forms Removal

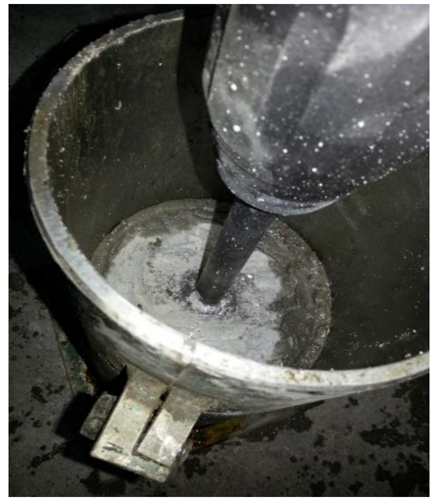
Fig -9 Curing Method of the Specimens

3.8 Hardened concrete tests

3.8.1 Compressive strength

A set of three specimens of each mix were tested for compressive strength at (3), (7), (28) days age. All cylinders were capped at the top surface which exposed to the disk of the testing machine according to (ASTM C 617-98) [18].

3.8.2 Erosion resistance test



The samples after 28 days has been taken out form the water, then were weighted in SSD condition then were put in the erosion testing machine. The samples were weighted regularly each day to measure the total erosion. The erosion was computed by the difference in weight of saturated surface dry weight of the specimen before and after exposing them to water jets. These measurements have been done in three different conditions:

3.8.2.1 Erosion resistance test under 3 bars pressure (by using Tap Water):

The 12 samples of Mix A have been tested with 3 bars pressure using normal tap water. The samples were weighted daily through 30 days of exposure to the water jets and no significant weight differences were found with the balance of 1gm accuracy. We repeated all the process for another 30 days using a balance of 0.1 gm accuracy. Again the results were not significant, the differences between the readings were very small.

3.8.2.2 Erosion resistance test under 5 bars pressure (by using Tap Water)

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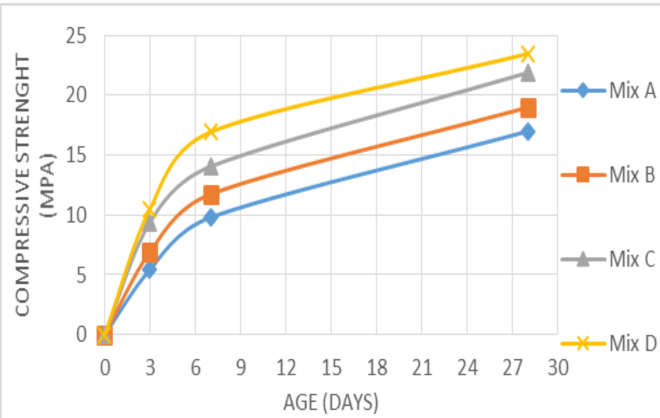
The erosion test has been repeated by increasing the pressure of the water jets to 5 bars by closing 8 nozzles and make only 4 of them operating. The process continued 20 days and the results were again insignificance (very small values)

3.8.2.3 Erosion resistance test under 5 bars pressure (by using Water containing sand particles).



In order to increase the severity of the erosion we repeated the test by using water containing sand particles (water borne particles). After a week, there was a visually eroded face with very little weight differences. The water pump cannot endure the movement of the sand particles through it so it was burned.

A new water pump for industrial use (heavy duty) was replaced. The new water pump had higher efficiency. The pressure in the system can be regulated to 5 bars for all 12 nozzles. The instrument was modified to assure the circulation of the water with the sand particles. This modification was done by making the bottom of the tank inclined against the intake of the pump.

The quantity of sand used was 100 kg/ 1m3 of water. The grading of the sand used was fixed to 0.3 mm in order to be able to move with the circulation of the water through the pipes and the pump. The pipes were opened twice weekly in order to remove any sedimentation of the sand that may happen.

The differences between the weight of the samples gained after 1, 3 and 7 days were noticeable.

The same procedure was used for the other two mixes of RCC and also for the conventional concrete mix.

4. Results and Discussions

4.1 Workability test results:

Slump test was done for all RCC mixes with different water cementitious ratio (W/CM) and for conventional concrete. All roller compacted concrete mixes had zero slump value while the conventional concrete had 8 cm slump.

The consistency for each mix of roller compacted concrete was measured by Vebe apparatus and the results of the Vebe time are shown in table-3

Table -3: Consistency Test Results

mixes	Results	Limits			
	Modified Vebe time (sec.)	Stiff (sec.)		Extremely Dry (sec.)	
A	25	5	10	18	32
B	31.2	5	10	18	32
C	32	5	10	18	32

The results of the RCC mixes fall in the extremely dry zone with Vebe time ranges from 25 to 32 seconds.

4.2 Compressive strength results

The 28-day compressive strength results of both RCC and conventional concrete specimens for each mix of RCC are shown given in the Fig -10.

Fig -10 Relationship between Compressive Strength and Time

From fig.10, we can see that the conventional concrete has the highest strength development values and that is due to the higher cement content. The results of the compressive strength of the roller compacted concrete mixes were found to be with respect to the water cementitious ratio.

4.3 Erosion testing results

4.3.1 Erosion resistance test under 3 bars pressure of tap water

The test was repeated 30 days using a balance of 0.1 gm accuracy with continuous weighting of the samples. The average results of the erosion are presented in table -4. The results of the 12 samples of Mix A which is roller compacted concrete of (W/CM=0.7) exposed to jets of tap water under 3bars pressure for 30 days (continuously) under different angles of projection were insignificant

Table -4: Results of Average Erosion under 3 bars for 30 Days

Mix	Water Projection Angles			
	90 º	60 º	30 º	0 º
Erosion (gm) Mix A	0.3	0.8	1	0.2

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4.3.2 Erosion resistance test under 5 bars pressure of tap water

It is obvious form table -5, that the values of the erosion under higher pressure (5 bars) of tap water jets with different angles are still very small values and may need very long time in order to get some significant results.

Table -5: Results of Average Erosion under 5 bars for 30 Days

4.3.3 Erosion resistance test under 5bars pressure water containing sand particles (water-borne particles).

4.3.3.1 Erosion trend and general results

The total erosion results gained by using water borne particles under pressure of 5 bars for the four mixes, for different angles and for the three intervals (1, 3 and 7 days) are illustrated in Fig -11.

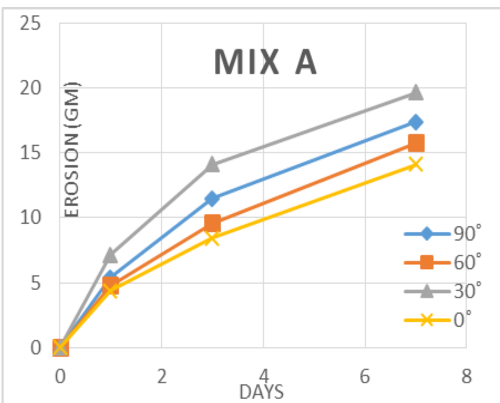


Fig -11 Trend Erosion of the Mixes

It is clear from Fig.11 that the values of erosion of the conventional concrete mix in general are the least values for all exposure intervals. The roller compacted mixes having greater water to cementitious material ratio had greater erosion values. This can be attributed to the strength of the cement paste at these exposure interval. As the cement content in the conventional concrete is greater than other RCC mixes then; the cement paste is stronger and thus can be less affected by the water jets.

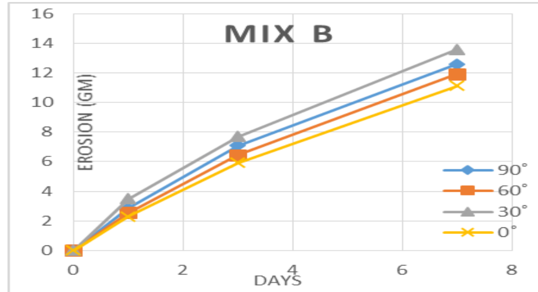
4.4.3.2 Total erosion of concrete mixes under different

Mix	Water Projection Angles			
	90 º	60 º	30 º	0 º
Erosion (gm) for Mix A	2.4	1.2	2	1

angles of projection

Fig -12 Total Erosion at Different Angles for Mix A

Fig -13 Total Erosion at Different Angles for Mix B



(W/CM=0.7)

(W/CM=0.65)

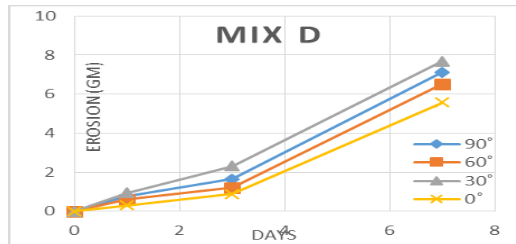
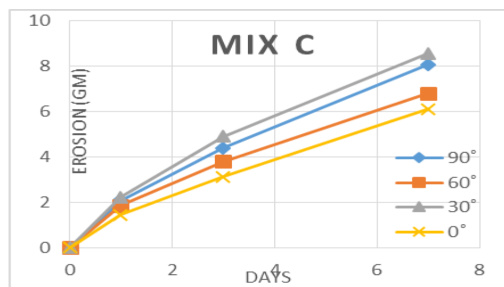


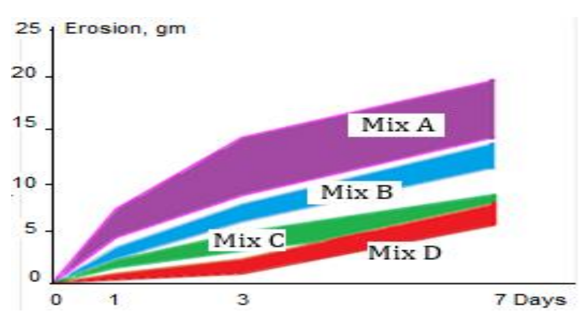
Fig -14 Total Erosion at Different Angles for Mix C

Fig -15 Total Erosion at Different Angles for Mix D

(W/CM=0.6+S.P)

(Conventional Concrete W/C=0.6)





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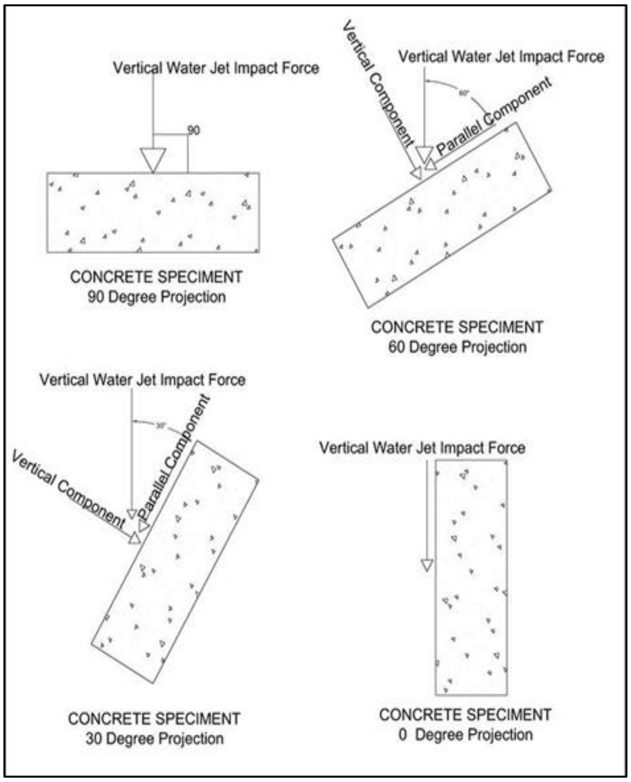
We believe that the erosion of the concrete surface is a result of one or more than one of the following forces; impact, cavitation and abrasion. The impact jet force for all the angles can be analyzed into two components, one is perpendicular to the surface of the specimen which has an impact erosion action and the other is parallel to the surface



of the specimen and usually has abrasion and washing effect as shown in Fig. 16.

Fig -16 The Impact Jet Forces for All the Angles

The results showed that the erosion value is higher at 30° degrees projection. That can be attributed to the perpendicular component (which presents about 50 % of the jet impact vertical force) which has impact erosion effect in addition to the effect of the parallel force (which present about 86 % of the jet impact vertical force) which can mainly be abrasion and washing effect.

5. Conclusion

This study set out with an aim to facilitate the difference between different water cementitious ratio mixes of roller compacted concrete and with the conventional concrete in hydraulic structures with regard to erosion. From this study "effect of water movement conditions on erosion of roller compacted concrete" the following conclusions are found:

1. Studies on an erosion effect on concrete in hydraulic structures are limited nationally and internationally.
2. As the compressive strength of the roller compacted concrete was increased the erosion resistance was increased also.
3. At exposing Mix A (W/CM=0.7) to tap water pressure (3 bars and 5 bars) for periods of 30 days, no significant erosion was found at all the four angles of projections.
4. By increasing only the water jet pressure of tap water, we cannot get significant erosion unless we change the properties of the projected water. That was done by adding sand particles and thus the water became water-borne particles.
5. The trend of erosion of conventional concrete shows that the rate of erosion at early days of exposure (1-3 days) was smaller than that at the later days (3-7 days). That may explain why some of the researchers found that the erosion of roller compacted concrete is smaller than of that of conventional concrete.
6. Results of water-borne particle jets show that the erosion of all roller compacted concrete mixes and conventional concrete mixes was related to the angle of projection of the water jet. The highest erosion was achieved at 30 degrees then the smaller was at 90 degree then at 60 and the least erosion was found at 0 degree.

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