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Abrasion erosion of concrete by water-borne sand

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Abstract

Hydraulic concrete structures frequently experience long-term abrasive erosion by water-borne sand, resulting in surface damage and eventually limiting their service life. In this study, the investigation of abrasion erosion tests on concrete with various water to cementitious material ratios (w/cm) was performed. The effects of the constituent materials on concrete structure abrasion erosion resistance were studied. The test results show that: (1) reduction in the w/cm ratio increases the tested concrete abrasion resistance; (2) the splitting tensile strength is a viable indicator for concrete abrasion resistance; (3) high permeability concrete exhibits weak abrasion resistance; and (4) concrete and low strength concrete made with coarser aggregate exhibit greater abrasion resistance.

Keywords: Abrasion erosion; Splitting tensile strength; Compressive strength; Permeability

1. Introduction

Abrasion erosion damage is caused by friction and the impact of water-borne silt, sand, gravel, rocks, ice and other debris on the concrete surface of a hydraulic structure [1]. Spillway aprons, stilling basins, sluiceways, drainage conduits or culverts, and tunnel linings are particularly susceptible to abrasion erosion resulting in surface fractures, concrete peeling and corroded reinforcing bars [1–3].

In general, the chronological sequence of abrasion progresses in three stages as shown in Fig. 1. First, pre-abrasion peeling occurs from water molecules closely related to the flow velocity and associated hydraulic pressure (Fig. 1a). Second, solid particle impacts, governed by the particle size of water-borne solids, produce interface cracking in the concrete (Fig. 1b). Finally, abrasive erosion action that is intimately associated with the combined water-borne particle hardness, flow velocity and interfacial bonds of concrete constituents (Fig. 1c) [4]. Abrasion erosion is caused not only by water-borne particles. There are other culprits as shown in Fig. 1.

Fig. 2 illustrates the chronological abrasion of a concrete surface subject to long-term hydraulic impingement by water-borne sand. In the beginning, the mortar surface layer is gradually worn down and the coarse aggregate subsequently exposed. Next, the coarse aggregates are fractured or plucked away by water-borne particle impacts. This results in the formation of tiny voids in the mortar along aggregate surfaces. The continuous mortar wearing results in coarse aggregate exposure. The formation of voids is profoundly influenced by the coarse aggregate size, type of sand used and the momentum of the rotating water-jets that penetrate further into the interior region of the concrete body. The interfacial binding mechanisms between the coarse aggregate and mortar influence the abrasion resistance of a hydraulic concrete structure.

2. Standard test methods

Over several decades, numerous investigations have been carried out to examine concrete abrasion resistance by many investigators. Interestingly, their test results varied remarkably as different test procedures were used. The following briefly summarizes the test methods that have been commonly applied:

(1) The ASTM C418, Standard Test Method for Concrete Abrasion Resistance to Sandblasting. This test involves

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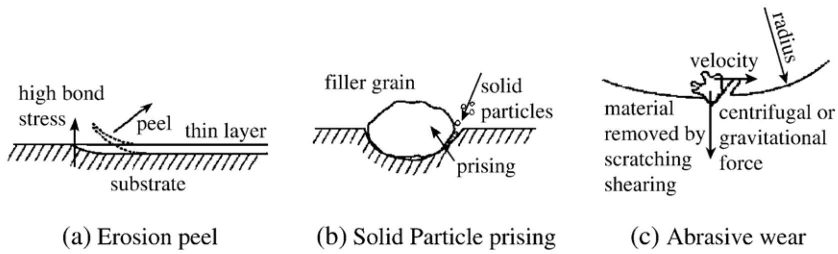


Fig. 1. Applied stresses from water-borne sand on concrete surface [4].

the use of Ottawa sand to sandblast a test specimen [5]. The shortcoming of this method involves the sand particle size used in creating water-jet impacts. This sand is too fine to produce impact energy close to that of an actual water-borne particle flow in the field.

(2) The ASTM C779, Standard Test Method for Horizontal Concrete Surface Abrasion Resistance. This procedure assesses both the impact and shear on a concrete test slab by exerting a designed rotating water pressure [6]. Laplante and his team carried out related tests in 1991 using a modified apparatus to generate impact forces stronger than the conventional one used in the ASTM C779 standard procedure. The test results revealed that using silica fume and coarse aggregate improved the concrete abrasion resistance. The abrasion resistance of concrete depends closely on the abrasion resistance of its constituent coarse aggregate and mortar [7].

(3) The ASTM C944, Standard Test Method for Concrete or Mortar Surface Abrasion Resistance using the Rotating-Cutter Method. This procedure uses an abrasive wheel placed in a drill-press held against the test surface at a designated pressure for a prescribed period of time [8]. This test has been successfully used in establishing highway and bridge concrete surface quality control. However, similar tests for hydraulic concrete have not yet been reported. The test results indicate that using silica fume, latex and carbon fibers in concrete significantly improves the mortar abrasion resistance because these additives proportionally increase the modulus elasticity and tensile strength of concrete thus made [9].

(4) The ASTM C1138, Standard Test Method for Concrete Abrasion Resistance (Underwater Method). Wearing action produced using steel-wheeled trolleys has been widely used in pavement applications [10]. This test method is capable of simulating the friction, but not impact, of water-borne particles on concrete surfaces. The test results show that the abrasion resistance increases with respect to higher compressive strength and a lower water/cement ratio. A significant correlation has been found between concrete abrasion resistance, aggregate hardness and mortar made with silica fume [11,12].

(5) The Grit-blasting Abrasion Erosion Test Procedure. This method involves the use of tiny grains (average size is 165 μm) to grit-blast a small area in a test specimen. The shortcoming of this method is the inability to reveal the interfacial bonds between coarse aggregate and mortar in a small concrete specimen. The test results indicate that the abrasion rate depends remarkably on the grit-blast impact angle. This method cannot show the mortar and concrete compressive strength effects on abrasion erosion [13,14].

A literature review on the standard concrete test methods and experiments was carried out to determine the frictional attrition involving water flow impingement containing limited amounts of granular material on small concrete surface areas. The above methods can be improved by applying a water-jet containing a proper amount of sand to simulate the concrete abrasion erosion that actually takes place in the field. The proposed test method in this study was, therefore, designed to include test elements not included in the aforementioned test methods to yield realistic abrasion data for future design applications.

3. Proposed test method

3.1. General description

Because concrete abrasion resistance is considered as the primary factor in determining the service life of a hydraulic structure, appropriate testing methods and suitable materials for making specimens became the paramount concern of our investigation. To accurately model the damage mechanisms, a carefully thought-out test procedure was developed by combining the water-jet impact load and sand particle shear/friction forces produced by a hydroparticle flow.

In this study, water-borne abrasion over a large area of the test slab was conducted. To realistically simulate the materials used in

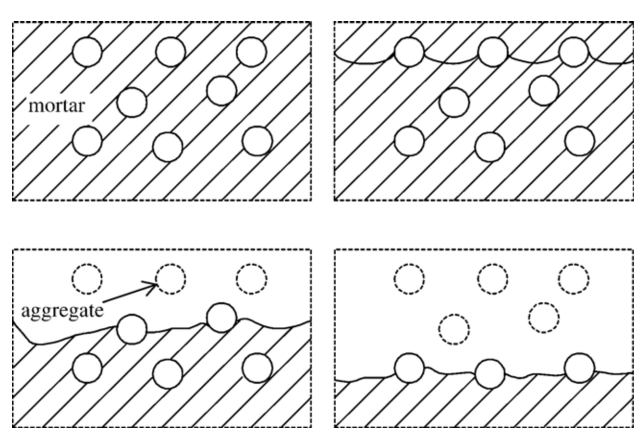


Fig. 2. Abrasion erosion process of hydraulic concrete surface.

Table 1
Mixture properties (kg/m^3)

Mixture	w/cm	Water	Cement	Fly ash	Coarse aggregate	D_{max} (mm)	Sand	Superplasticizer
C50a	0.50	160	320	0	0	5	795	0
C50b	0.50	160	320	0	1073	13	795	0
C50c	0.50	160	320	0	1073	25	795	0
C36W14	0.36	140	331	58	1030	13	815	10.9
C36W16	0.36	160	378	67	968	13	763	12.4
C36W18	0.36	180	425	75	917	13	724	10.0
C32	0.32	140	328	109	1070	13	720	11.4
C28a	0.28	140	350	150	0	5	690	15.0
C28b	0.28	140	350	150	1030	13	690	15.0
C28c	0.28	140	350	150	1030	25	690	15.0

hydraulic structures, various concrete slabs were made with various water/cementitious material ratios (w/cm), different water content and maximum aggregate size for this investigation. Pilot tests were conducted prior to the designed tests to ensure the developed procedures would serve the intended purpose.

3.2. Specimens

3.2.1. Materials

The materials used in manufacturing the test slabs include: (a) Type I Portland cement (ASTM C150); (b) Class F fly ash with a specific gravity of 2.31, supplied by the Tai Chung Power Plant of the Taiwan Power Company; (c) river sand with a fineness of 2.95, specific gravity of 2.64 and absorption rate of 1.2%; (d) crushed basalt coarse aggregate with a maximum aggregate size (D_{max}) of 13 mm or 19 mm, specific gravity of 2.64, absorption of 1.0% and dry-rod densities of 1630 and 1665 kg/m^3, respectively. (e) Superplasticizer (SP) conforming to ASTM C494 Type-G with a specific gravity of 1.1; and (f) fresh water.

3.2.2. Mixture proportions

Four w/cm ratios of 0.50, 0.36, 0.32, 0.28 and 3 maximum coarse aggregate sizes (D_{max}=5, 13, 25 mm) were selected to make concretes that are commonly used in hydraulic structure construction. Based on a careful study, 10 different mixture proportions were designed to meet the test requirements. The mixing details are presented in Table 1.

Proper amounts of pozzolanic fly ash were used to replace 30 wt.% of the cementitious materials used in the 10 mixture designs to minimize hydration heat that has been suspected as the possible cause for concrete microcracks.

3.2.3. Casting

For each concrete mix, the following specimens were cast: (a) six 152×305 mm (6×12 in.) cylindrical specimens for compressive strength testing were made and tested in accordance with ASTM C39; (b) six cylindrical specimens were made for splitting tensile strength test and tested in accordance with ASTM C496; (c) six prisms, 100×100×383 mm, were produced for the flexural strength test and tested in accordance with ASTM C78; (d) six 100×200 mm cylindrical specimens for the permeability test and tested in accordance with JIS A1404; (e) six square slabs, 200×200×50 (thick) for the abrasion test. The measured average abrasion rate of three plates was designated as the representative data for each concrete mix for reference use.

Immediately after the slabs were cast, the cylinders and prisms were cured in a humidity-controlled room for 28 and 56 days, respectively, until ready for the abrasion tests. Table 2 lists the measured mechanical properties, and Table 3 lists the measured abrasion erosion rate of the produced concrete specimens.

3.3. Abrasion test procedures

The test method developed in this program was specifically designed to evaluate the abrasive resistance of concrete surfaces subjected to water flow impact and sand impingement. To understand the interfacial bonding behaviors between coarse

Table 2
Mechanical properties of concrete

Mixture	Compressive strength MPa (psi)		Flexural strength MPa (psi)		Splitting tensile strength MPa (psi)		Permeability coefficient (×10^{-10} cm/s)	
	28 days	56 days	28 days	56 days	28 days	56 days	28 days	56 days
C50a	18.6±0.6 (2700)	19.8±0.8 (2870)	2.6±0.1 (377)	3.2±0.1 (464)	0.9±0.06 (131)	3±0.1 (189)	2.87±0.19	2.70±0.20
C50b	24.0±0.9 (3480)	26.3±1.1 (3810)	3.9±0.2 (569)	5.7±0.3 (827)	2.3±0.2 (334)	2.8±0.4 (406)	2.41±0.15	1.95±0.13
C50c	26.7±1.0 (3870)	29.7±1.1 (4310)	4.3±0.3 (624)	5.2±0.5 (754)	2.8±0.3 (406)	3.1±0.3 (450)	2.26±0.12	1.86±0.15
C36W14	49.5±1.8 (7180)	56.8±2.0 (8240)	8.5±0.6 (1230)	9.0±0.9 (1305)	3.9±0.3 (566)	4.6±0.3 (667)	1.94±0.12	1.13±0.10
C36W16	48.6±1.8 (7050)	52.9±1.9 (7670)	8.1±0.6 (1175)	8.7±0.6 (1262)	3.7±0.2 (537)	4.5±0.5 (653)	2.08±0.15	1.29±0.12
C36W18	44.3±1.5 (6425)	48.7±1.6 (7060)	7.9±0.6 (1146)	8.3±0.5 (1204)	3.5±0.3 (508)	4.1±0.4 (595)	2.17±0.16	1.69±0.16
C32	64.5±2.5 (9355)	72.6±3.0 (10,530)	9.6±0.6 (1392)	10.1±0.7 (1465)	4.7±0.4 (682)	5.1±0.6 (740)	1.53±0.11	0.83±0.09
C28a	91.2±3.8 (13,230)	92.6±3.2 (13,430)	10.7±0.6 (1552)	11.9±1.2 (1726)	5.8±0.5 (841)	6.2±0.5 (899)	1.16±0.12	0.87±0.07
C28b	90.3±3.8 (13,100)	92.4±4.1 (13,400)	11.0±0.9 (1595)	12.0±1.0 (1740)	5.8±0.6 (841)	6.3±0.3 (914)	1.05±0.09	0.78±0.07
C28c	88.5±3.7 (12,835)	89.3±3.8 (12,950)	10.3±0.5 (1494)	11.6±0.9 (1682)	5.4±0.4 (783)	6.1±0.6 (885)	0.94±0.06	0.79±0.09

Table 3
Abrasion erosion rate of concrete

Mixture	D_{max} (mm)	Water content (kg/m^3)	Abrasion erosion rate (ER) at 180 min (g/min)	
			28 days	56 days
C50a	5	160	0.603±0.070	0.536±0.052
C50b	13	160	0.433±0.041	0.348±0.036
C50c	25	160	0.399±0.036	0.330±0.035
C36W14	13	140	0.336±0.029	0.290±0.020
C36W16	13	160	0.350±0.032	0.309±0.026
C36W18	13	180	0.361±0.031	0.316±0.033
C32	13	140	0.285±0.026	0.255±0.024
C28a	5	140	0.205±0.015	0.192±0.021
C28b	13	140	0.216±0.017	0.190±0.017
C28c	25	140	0.234±0.027	0.196±0.018

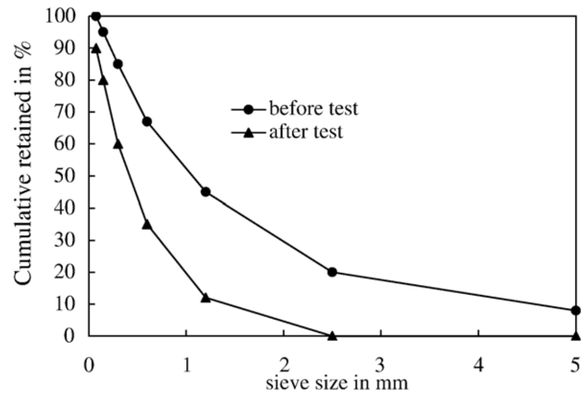


Fig. 4. The sand size distribution of the used sand material.

aggregate and mortar, a specially designed and fabricated 10×200 mm rectangular nozzle large enough to cover the maximum aggregate size was used in the shotcrete tests. The reason a rectangular nozzle was used is that it produces a water-jet flow that simulates the water flow over a spillway in the field.

The test water was made by mixing quartz tic river sand not coarser than 5 mm to formulate a slurry mixture. During the tests, the nozzle was held at a 45° angle to the test slab to optimize the impact and shear forces.

An abrasion chamber measuring 2500×1800×1500 mm, capable of accommodating four individual pumps that simultaneously expended four separate water flows with different sand mixtures at different velocities onto the test slab, was positioned above the water level, as shown in Fig. 3.

A fresh supply of sand was used to make the designed water flows composed of angular quartz tic river sand with a Mohs-hardness (H_p) of 8 and density (ρ_p) of 2.64 g/cm^3. The size distributions before and after the test are shown in Fig. 4. The sand was gradually poured and mixed for 5 min until the mixture reached 400 kg/m^3 sand content.

During each water-jet test, the number of cavities were assessed and found to be 0.2. In accordance with a previously published paper, the erosion effect of 0.2 cavities is small enough to be ignored [15]. Throughout the 3-h water-jet test, the water velocity was controlled at 10 m/s, equivalent to a 0.17 MPa pressure on the test slab. The water temperature was maintained at 30 °C.

At the end of the test, significant abrasion erosion became visible on the test slab surfaces. Immediately after the test, the loose materials were flushed off and collected to determine the eroded material weight with a precision of ±0.05 g. The slab weight, before (m_1) and after (m_2) the test, was also measured to determine the abrasion erosion rate, E_R:

$$E_R = \frac{m_1 - m_2}{t}$$

E_R is given in g/min in which a greater value signifies weaker tested concrete abrasion erosion resistance.

4. Test results and discussion

4.1. Influence of w/cm ratios on abrasion erosion resistance

Fig. 5a shows the surface of a tested concrete slab made with w/cm=0.36 after 3 h of water-jet testing. The exposed coarse aggregates suffered minute abrasion compared with the surrounding mortar on which interfacial cracks are visible. These cracks are attributed to the high w/cm ratio. Conversely,

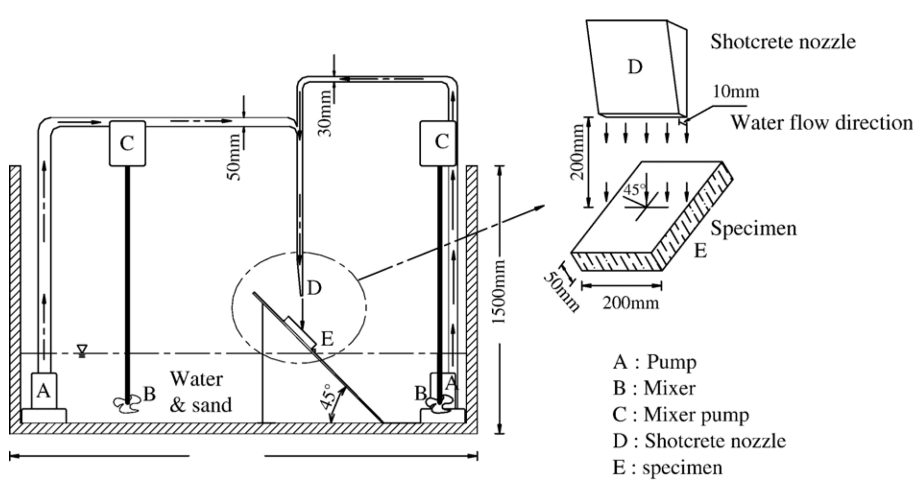
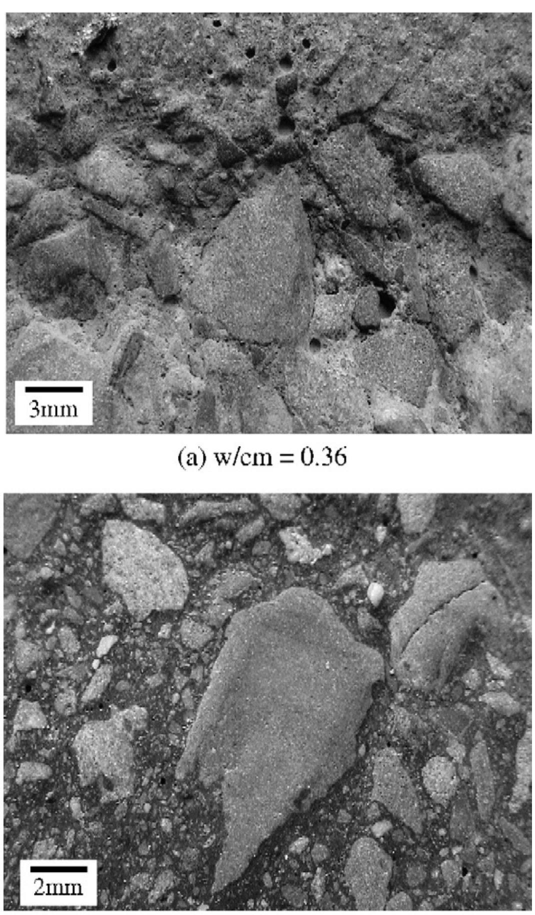


Fig. 3. Water-borne sand abrasion erosion test apparatus.

the surface of a tested slab made with a w/cm ratio of 0.28, shown in Fig. 5b, appears to be quite smooth. This difference is explained by the w/cm ratio principle that claims a higher strength for concrete made with a lower w/cm ratio. In this case, the mortar strength is comparable to that of the coarse aggregate. Both test slabs were subjected to the same abrasive forces in the water-jet test. Because of the equivalent peeling and grinding on aggregate and mortar leading to the tested slab appears to be relatively smooth.

A conclusion can be drawn from the test results that concrete abrasion resistance is in inverse proportion to the w/cm ratio used. Concrete with a low w/cm ratio develops less porosity, higher strength and a stronger interfacial bond in the hardened mortar and thus enhances the overall concrete abrasion erosion resistance performance.

Fig. 6 shows the w/cm ratio and abrasion erosion rate relationship. It shows that the w/cm ratio increases from 0.28 to 0.36 and then to 0.50. The abrasion erosion rate increases proportionally by approximately 45% and 76%, respectively. An interesting issue concerning porosity deserves the readers' attention. Concrete with higher porosity can be easily worn by a water-jet and subsequently develops additional porosity, producing an undesirable cycling effect. In contrast, low w/cm concrete that is made by adding fly ash as a micro-filler substantially reduces the porosity, pore sizes and strengthens the bond among particles of the hydrated matrix [16]. A low w/cm concrete will exhibit better abrasion erosion resistance.



(a) w/cm = 0.36

(b) w/cm = 0.28

Fig. 5. Surface profile of concrete after abrasion erosion.

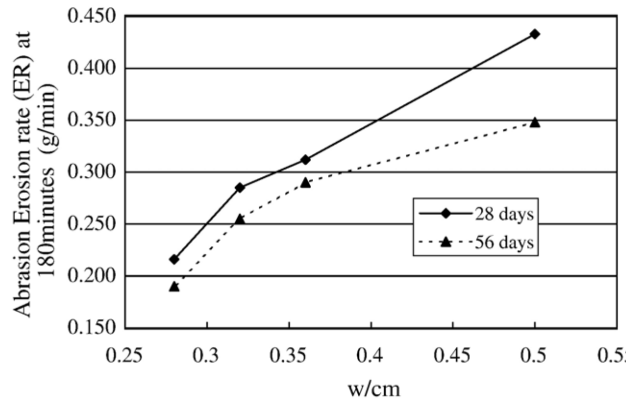


Fig. 6. The relationship of w/cm and abrasion erosion rate.

4.2. Effects of permeability and strength

Permeability is closely related to porosity. The permeability effect on abrasion erosion was explained in the previous section. As the porosity of the concrete paste decreases, the concrete becomes more impermeable. Fig. 7 illustrates the relationship between the permeability coefficient and abrasion erosion rate. This is nearly a linear relationship. For concrete, the permeability coefficient increases with the increase in the concrete abrasion erosion rate. It is noteworthy to point out that concrete made with a high w/cm ratio and small maximum aggregate size increases the permeability coefficient.

When a test slab is subjected to a water-jet, the impacts conceivably induce compressive, tensile and shear stresses near the top surface of the test slab. It is clear that the concrete strength has a profound effect on the abrasion resistance of the test concrete. Figs. 8, 9 and 10 illustrate the relationships between the abrasion erosion rate, compressive strength, splitting tensile strength and flexural strength, respectively, for 3-h water-jet tests. In general, the abrasion rate decreases when the concrete strength increases. In other words, the abrasion resistance increases with the increase in concrete strength. Coefficients of determination (R^2) are often applied to correlate the concrete strength with the

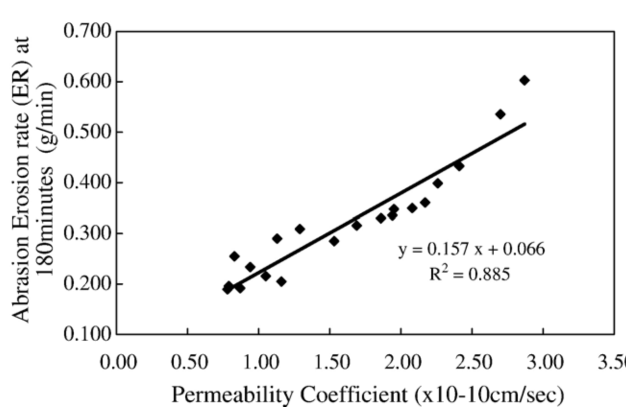


Fig. 7. The relationship of permeability coefficient and abrasion erosion rate.

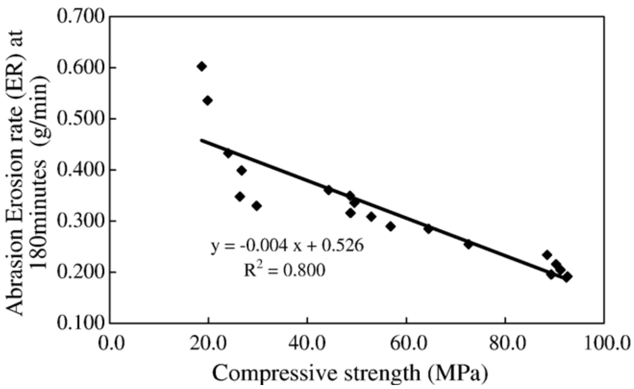


Fig. 8. The relationship of compressive strength and abrasion erosion rate.

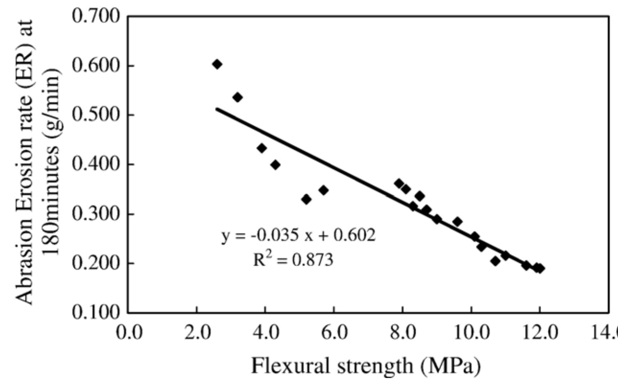


Fig. 10. The relationship of flexural strength and abrasion erosion rate.

abrasion rate. The computed R^2 for compressive, splitting tensile and flexural strengths are 0.800, 0.947 and 0.873, respectively, as shown in the figures.

Slab observations after being subjected to water-borne sand jet tests reveal that transient hydraulic rim-pulls impinged on the test slab and caused local tensile stresses in the top layer of the exposed concrete. Based on the energy conservation theory, the tensile stress intensities varied with the hydraulic jet force impact momentum.

These tensile stresses are the prime culprit causing micro-cracks in the hardened mortar and fractures around the aggregate particles, eventually leading to abrasion erosion.

As we know, there is nothing that can slow such abrasion erosion except strengthening the concrete mechanical properties, i.e., the concrete compressive, tensile, splitting tensile and flexural strengths.

4.3. Effects of coarse aggregate and water content

Since coarse aggregate is the dominant material in concrete, aggregate selection is an important factor in conjunction with the concrete abrasion resistance. As previously discussed, coarse aggregate near the top surface of a test slab is often plucked away by water-borne sand jet flow, creating scattered voids in the concrete surface. As the jet flow continues, loose sand enters the voids and swirls swiftly. This hydraulic force enlarges the voids from the water-borne sand friction. The void walls are subsequently ruptured, forming larger voids. The mortar bond strength, quality and coarse aggregate size are the governing factors for concrete abrasion erosion resistance.

The following is a discussion on water content. The data in Table 3 reveals the relationship among the water content, coarse aggregate and abrasion erosion rate. Under a fixed w/cm ratio, an increase in water content will increase the amount of cementitious material and decrease the coarse aggregate content. An increase in the water content increases the abrasion erosion rate.

Table 3 provides the average abrasion erosion rate of concrete made with a w/cm ratio of 0.36. Results show that, if the water content is increased from 140 kg/m^3 to 180 kg/m^3, the coarse aggregate content decreases from 39% to 36%, resulting in an increase in the abrasion erosion rate by approximately 7% to 9%. Fig. 11 shows the void formation attributed to bleeding, cracks along the interfaces between the coarse aggregate and mortar, and indentations on the mortar surface. Concrete made with high water content reduces the abrasion erosion resistance. This is attributed to the reduction in coarse aggregate volume and bond strength caused by bleeding water.

The abrasion test results of low strength concrete (w/cm = 0.50) made with different maximum coarse aggregate size are shown in Table 3. A maximum coarse aggregate size, $D_{\max}$, greater than

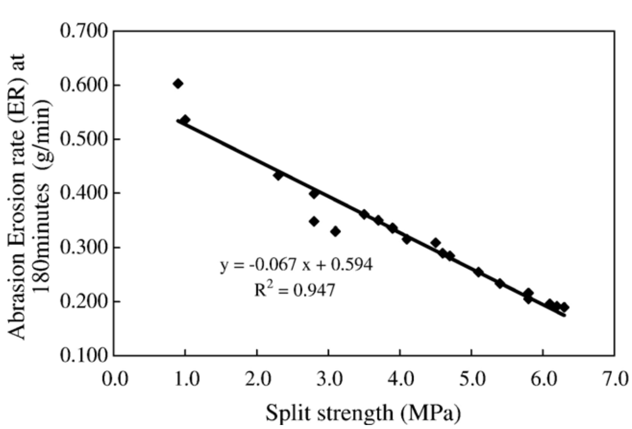


Fig. 9. The relationship of splitting tensile strength and abrasion erosion rate.

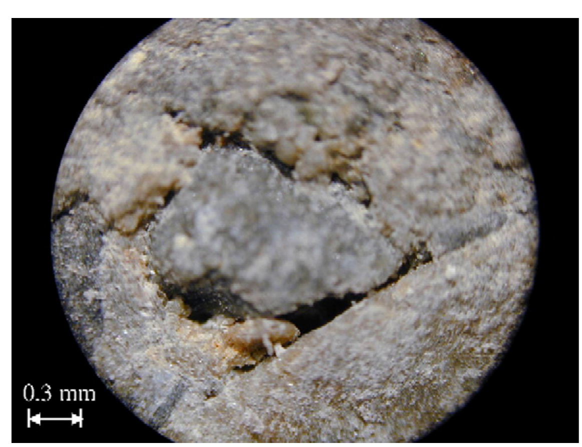


Fig. 11. The cracks on the interface of the aggregate and cement paste with w/cm = 0.50.

13 mm increases the abrasion erosion resistance and the resistance decreases when D_{max} is equal to or smaller than 5 mm.

A concrete mix engineering principle can be used to explain the relationship stated above. Low strength concrete paste used together with small sized aggregate generally requires a greater amount of cement paste to cover the aggregate surface area. The lower strength and larger interfacial aggregate area jointly make the concrete more vulnerable to abrasion erosion.

Accordingly, for concrete made with a w/cm ratio of 0.50, the decrease in maximum aggregate size will decrease its abrasion erosion resistance. Conversely, in high strength concrete made with a w/cm ratio of 0.28, the maximum aggregate size effect on the abrasion erosion resistance appears to be insignificant.

5. Conclusion

This experimental study enabled us to understand the practical problems associated with hydraulic structures and seek viable engineering solutions for these problems. Our findings are summarized as follows:

(1) Test method—the test procedure developed in this study is practical for concrete abrasion resistance experimental evaluations using water-jets with water-borne sand.
(2) Concrete materials—concrete slabs made with mineral admixtures such as fly ash strongly enhance the abrasion resistance attributed to mortar densification, bleeding void reduction and interfacial bond strength improvement. The measured data illustrates that the abrasion erosion rate increased approximately 76% when the w/cm ratio was changed from 0.28 to 0.50. This is a tremendous improvement.
(3) Test data—the data obtained indicated that the splitting tensile strength is a more effective predictive factor than compressive and flexural strength in determining concrete abrasion erosion resistance to water-borne sand.
(4) Water content—concrete made with a w/cm ratio of 0.36, for example, showed increased abrasion erosion rate by approximately 8% when the water content was increased from 140 to 180 kg/m^3.
(5) Coarse aggregate—for low strength concrete made with a w/cm ratio of 0.50 and coarser aggregate, with a maximum size up to 13 mm, improved the concrete abrasion erosion resistance. For high strength concrete, the coarse aggregate size effect on the concrete abrasion erosion appeared insignificant in comparison with the low strength concrete erosion.

Acknowledgments

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References

[1] ACI Committee 210, Erosion of Concrete in Hydraulic structure (ACI 210R-03), ACI Manual Concrete Practice, Part 1, American Concrete Institute, Farmington Hill, MI, 2003.
[2] Chi Sheng Hsian, The Experiment and Treatment of Hydraulic Concrete, China Hydraulic and Power, Beijing, 1997.
[3] Creegan, et al., Erosion of concrete in hydraulic structure, ACI Materials Journal 184 (2) (1987) 136–157.
[4] David Plum, Fang Xufei, A rock and a hard place, Water Power and Construction, July 1996, pp. 30–33.
[5] The American Society for Testing and Materials, Standard Test Method for Abrasion Resistance of Concrete by Sandblasting, ASTM Designation C418-98, Philadelphia, 1999.
[6] The American Society for Testing and Materials, Standard Test Method for Abrasion Resistance of Horizontal Concrete Surfaces ASTM Designation C779-00, Philadelphia, 2000.
[7] P. Laplante, P.C. Aitcin, D. Vexina, Abrasion resistance of concrete, Materials in Civil Engineering 3 (1) (1991) 19–28.
[8] The American Society for Testing and Materials, Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method, ASTM Designation C944, Philadelphia, 1999.
[9] Zeng-Qiang Shi, D.D.L. Chung, Improving the abrasion resistance of mortar by adding latex and carbon fibers, Cement and Concrete Research 27 (8) (1997) 149–1153.
[10] The American Society for Testing and Materials, Standard Test Method for Abrasion Resistance of Concrete (Underwater Method), ASTM Designation C1138, Philadelphia, 1997.
[11] T.C. Liu, Abrasion resistance of concrete, ACI Journal 78 (5) (1981) 341–350.
[12] T.C. Holland, R.A. Gutschow, Erosion resistance with silica fume concrete, ACI Concrete International 9 (3) (1987) 32–40.
[13] A.W. Momber, The erosion of cement paste, mortar and concrete by gritblasting, Wear 246 (2000) 46–54.
[14] K.C. Goretta, M.L. Burdt, Solid-particle erosion of Portland cement and concrete, Wear 224 (1999) 106–112.
[15] K.H. Frizell, B.W. Mefford Jet, Designing spillways to prevent cavitation damage, Concrete International (May 1991) 58–64.
[16] Sidney Mindess, J. Feancis Young, David Darwin, Concrete, Second edition, 2002.