SOLID-PARTICLE ABRASION OF HYDRAULIC CONCRETE

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Abstract

Most of the abrasion damage is caused by the action of water-borne particles (silt, sand, gravel, and other solid) impacting and rolling against the concrete surface during hydraulic structure operation. In this paper solid-particle abrasion of concrete containing slag was studied. Experiments included use of angular river sand abrade of mean diameter ~ 0.6, 1.2, 2.5 and 5 mm impacting at 30°, 45° and 90° to the concrete surface. The waterborne sand flow impact test method was used. Test results show that the abrasion rate to be a strong function of erodent size. As the erodent size increased from 0.6 mm to 1.2mm, 2.5 mm, then to 5mm, the abrasion rate of concrete increased from 123% to 262% and 385%. Moreover, the abrasion rate of concrete impacted at 90° was higher than of that of 30° and 45°. Material loss in concrete appears to have been caused by a complex combination of fracture mechanisms.

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1. INTERDICTION

In Taiwan, all rivers originate from the peak of each ridge, snaking through valleys and running across sporadic plains to reach the ocean. Because of high ridge peaks and steep valley basins, all rivers are short and steep causing rapid flow during storms, particularly during the typhoon season. There is a high average annual rainfall of 2530 mm in Taiwan, approximate 2.6 times of world average rainfall. In addition, the type and space distribute of rainfall do not exceed each other much. The rainfall is concentrated in the month of May to October, where approximately 78 % of the average annual rainfall occurs [1]. Furthermore, because of the country's frequent earthquakes and fragile geology, the rapid flow of rivers carry heavy sand and gravel, making the sediment yield per area and sand percentage of river given more than ten times that of the world average. As a result, the most significant abrasion problems happen due to the abrasion effect of the friction and impact of waterborne sand on the hydraulic structures concrete surface.

When a brittle material is impacted by a hard sharp particle, the contact area is plastically deformed due to the high compressive and shear stresses and a radial crack is formed. After the impact, the plastic deformation leads to large tensile stresses that resulted in lateral cracks causing the material removal [2-3]. Abrasion condition and abrade characteristics also play key roles in determining abrasion rate. Large, hard particles are expected to import maximum abrasion rate. Large abrade particles flow much better than small one, and the debris that forms with import by larger abrades is larger [4]. Therefore, in this paper the waterborne sand flow test which combining the water-jet impact load and sand particle shear/friction forces produced by a hydro-particle flow, was used to investigated the effect of impact angle, abrade particles size on abrasion resistance of hydraulic concrete.

2. EXPERIMENTAL PROGRAM

2.1 Materials

Materials used in manufacturing test slabs include: (1) Type I Portland cement (ASTM C150); (2) river sand having a fineness of 2.95, a specific gravity of 2.64, and an absorption of 1.2 %; (3) crushed basalt coarse aggregate with a maximum aggregate size (D_{max}) of 13 mm, specific gravity of 2.64, absorption of 1.0 %, and dry-rodded density of 1665 kg/m^3, and (4) slag furnace with a specific gravity of 2.89 supplied by China Hi-Ment corporation; (5) superplasticizer (SP) conforming to ASTM C494 Type-G with a specific gravity of 1.1; and (6) fresh water.

2.2 Mixture proportions

The mixture proportions used in this investigation were designed to study the effect of abrasion type on concrete using the weight and absolute-volume method. As summarized in Table 1, for concrete mixtures were prepared with three different water-to-cementitious material ratios (w/cm) of 0.28 0.36 and 0.50. The cement was partially replaced with 20% of slag furnace by weight. A superplasticizer was used to produce concrete having roughly the same slump of 22±2cm. The compressive strength of concrete was shown in Table 1.

Table 1 - Concrete mix proportions and Compressive strength

Batch	*w/cm*	Dry quantities, kg/m^3						Slump (cm)	Compressive strength (MPa)
		Water	Cement	SF	Sand	Gravel	SP		
C28	0.28	160	457	114	730	925	12.5	24	90.8
C36	0.36	160	356	89	780	985	10.9	22	50.3
C50	0.50	160	256	64	820	1070	0.5	21	30.4

2.3 Experimental method

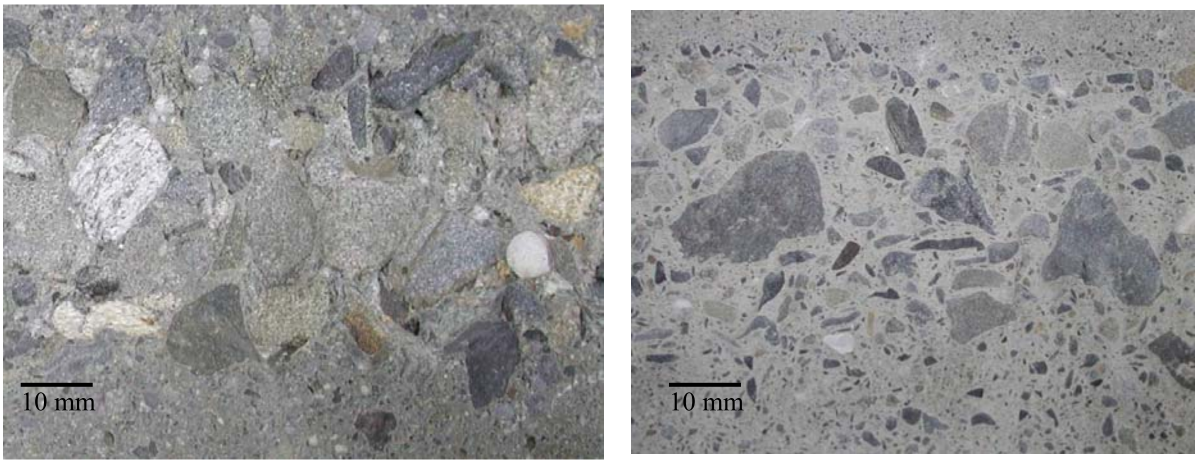
The abrasion tests were carried out in a waterborne sand flow apparatus that is described in Refs. [5-6]. The abrade particles were angular quartz tic river sand with a Mohs-hardness (H_p) of 8, density (ρ_p) of 2.64 g/㎝^{3} and mean diameters (D) of 0.6, 1.2, 2.5 and 5 mm, respectively. The waterborne sand flow velocity was 10±1 m/s and the angle of impact was 30°, 45° or 90°.

The abrasion rate (AR, in g/h) was determined from the specimen mass loss vs. test time. A minimum of three measurements were used to establish AR. The values of AR obtained are estimated to be accurate to ±15%. The larger error quoted here is attributable primarily to specimen uniformity, not reproducibility of the testing procedure.

3. RESULTS AND DISCUSSION

Observations on the specimen after being subjected to a waterborne sand jet test reveal that transient hydraulic rim-pulls impinged on the specimen and caused local tensile stresses in the top layer of the exposed concrete. Based on the energy conservation theory, the intensity of the tensile stresses varied in respect to the impact momentum of the hydraulic jet forces. These tensile stresses are the prime culprits for causing cracks in the hardened mortar and fractures around aggregate particles which eventually lead to impact abrasion.

Fig. 1 shows photos from various impact abrasions of the concrete after testing. The matrix exhibits significant indenting by the exposed erodent, the aggregate grain appears to peel away and the mortar on which interfacial cracks become visible on the concrete prepared with high w/cm and impacted at 90° (Fig. 1a), whereas it appears to be rather smooth in low w/cm concrete and impacted at 45° (Fig. 1b). The SEM revealed the cracks formed in the cement matrix and the interface between aggregate grain and cement matrix shown in Fig. 2a for concrete impacted at 90°. The cement matrix significant indenting by the abrodent, with concomitant smearing of the surface, and formation of many small cracks rather than a few large ones. In addition, the concrete impacted at 90° displayed a rougher and more rugged surface than concrete impacted at 45° and 30° (Fig. 2b, 2c).



(a) *w/cm* = 0.50, impacted at 90° (b) *w/cm* = 0.28, impacted at 45°

Fig. 1 Images of worn concrete surfaces under various conditions

Fig. 3 shows the relationship between impact angle and abrasion rate. From Fig. 3 it is evident that the impact angle of 90° has the highest abrasion rate, and the impact angle of 45° has the smallest one. For concrete made with w/cm of 0.36 and 0.50, and impacted at 90°, the abrasion rate was nearly 124 % and 207 % higher than that of 45°, respectively.

A fundamental approach was to obtain the brittle abrasion deals with material removal due to crack formation, while ductile abrasion deals with material removal due to cutting and plowing [7]. For concrete, it is generally considered that abrasion damage is the gradual removal of material caused by repeated deformation and cutting action. The theoretical analysis for cutting [8-9] shows that progressive cutting occurs at a given low impact angle, under which a particle may slip on a surface or it may retain some of its own impact energy after the impact, resulting in a decreased in material removal. Moreover, the abrasion rate is associated with the relation between the shear force to cut a mass of material and the material resistance indicated by the compressive strength or hardness. For the concrete impacted by waterborne sand flow the abrasion action mainly include pre-abrasion peeling by water molecules and its associated hydraulic pressure, solid particle impact, edge effect and prising. For the concrete specimen impacted at 90° the crack formation due to normal component of impact velocity dominated material removal, while impacted at 30° the cutting dominated material removal. For waterborne sand flow test, it can be found that the abrasive force due to

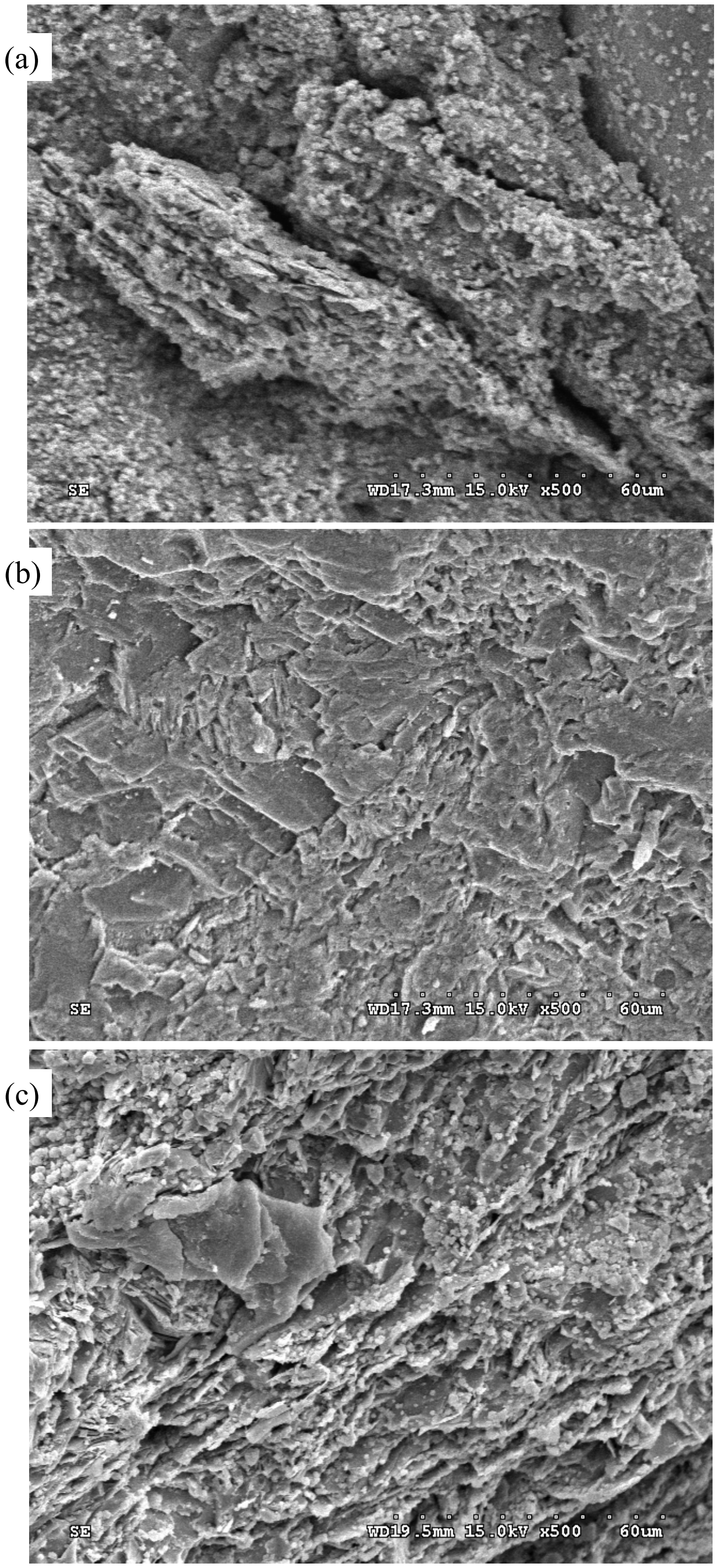


Fig. 2 SEM-images of worn concrete surface, scale: 60 μm. (a) impacted at 90°, (b) impacted at 45° and (c) impacted at 30°

normal component of impact velocity is higher than the cutting. With impact at 45°, SEM revealed that the indentation of the surface was insignificant compared with impact at 30° and 90°, reducing less material loss.

On the other hand, the abrasion rate is a strong function of erodent size as shown in Fig. 4. As the erodent size increased from 0.6 mm to 1.2mm, 2.5 mm, then to 5mm, the abrasion rate of concrete increased from 123% to 262% and 385%. When abrade size is decrease, eventually the abrade particles are not able to initiate cracking and will only plastically deform the target. Theories of abrasion of brittle materials, which are based on elastic-plastic interactions [10], predict AR α $D^{2/3}$. The experimental data for concrete specimens show a distinct relationship between the abrasion rate and the abrade size. It can be approximated by a non-linear regression of AR α $D^{3/2}$ with a regression coefficient of R^2=0.912. The deviations from the ideal are common and are usually related to interfacial, microstructural and flaw effects. Moreover, the water flow due to establishment of a stagnation pressure enters pre-existing flaws in the material, especially microcracks in the interfacial zones between paste and aggregate.

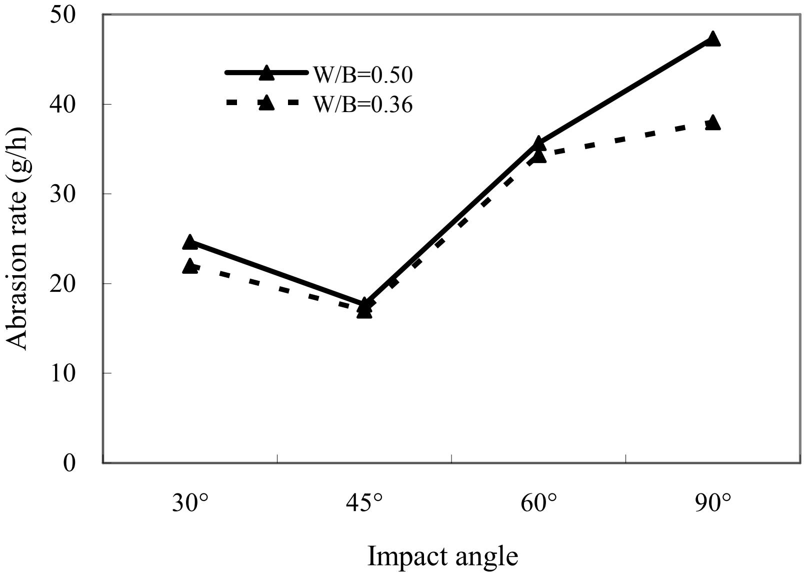


Fig. 3 Abrasion rate versus impact angle for concrete made with W/B= 0.5 and 0.36

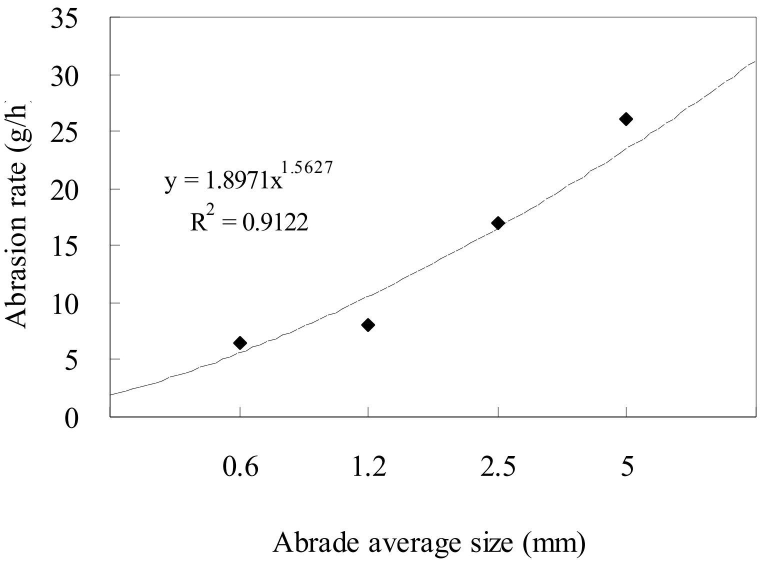


Fig. 4 Abrasion rate versus abrade average size for concrete made with W/B=0.36

4. CONCLUSSIONS

Solid-particle abrasion rate of concrete depended strongly on abrade size and impact angle. The abrasion rate was highest at 90° impact and lowest at 45° impact. As the erodent size increased from 0.6 mm to 1.2mm, 2.5 mm, then to 5mm, the abrasion rate of concrete increased from 123% to 262% and 385%. It can be approximated by a non-linear regression of AR α $D^{3/2}$ with a regression coefficient of R^2=0.912. For the concrete impacted by waterborne sand flow the abrasion action mainly include pre-abrasion peeling by water molecules and its associated hydraulic pressure, solid particle impact, edge effect and prising Material loss in concrete appears to have been caused by a complex combination of fracture mechanisms.

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