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Effect of sediment size on damage caused by cavitation erosion and abrasive wear in sediment-water mixture

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ABSTRACT

Damage caused by cavitation erosion and abrasive wear is a significant problem for hydraulic machinery in rivers with high concentrations of sediment. In this study, experiments are performed using a vibratory apparatus and a custom-made particle-moving device. The specimens are ASTM 1045 carbon steel, and sediment particles with mean diameters of 0.026–0.531 mm are mixed in water at concentrations of 25 kg/m^3, 50 kg/m^3, and 85 kg/m^3. Experimental results demonstrate that damage is indeed exacerbated with increasing sediment sizes. However, when the size of sediment particles is smaller than a critical number (D_c), the damage caused by the sediment-water mixture is slightly less than the cavitation damage caused by sediment-free water; furthermore, for this small sediment, the damage decreases as the concentration increases. The critical size for the cases in this study is approximately 0.035–0.048 mm. The viscosity of the mixture is likely a key factor to this phenomenon because the viscosities of mixtures with sediment smaller than the critical size increase as the sediment size decreases or the concentration increases. Experiments with mixtures with two sediment sizes further demonstrate that smaller sediment can inhibit the damage by cavitation.

1. Introduction

While sediment-containing fluid flows quickly through hydro-machinery such as piping, pumping equipment, and hydro-turbine, cavitation erosion and abrasive wear usually occur simultaneously, causing serious damage and substantial financial loss [1]. Erosive wear is caused by the impact of solid particles against the surface of a solid. The impacting particles gradually remove material from the surface through repeated deformations and cutting actions [2]. When a liquid is subjected to rapid pressure reductions, bubbles (cavities) form. Upon entering a high-pressure area, these cavities immediately implode [3,4]. If the implosion occurs on the surface of solid, shock waves and/or microjets generated by the collapse of the cavity cause damages to the surface.

The mechanism of cavitation and the resultant damage are complicated, and the physical properties of the liquid–particle flow—e.g., cavitation clouds [5], cavitation nuclei [6], vapor [7], and particles [8]—could induce more complex interactions. For example, particles can be significantly accelerated by growing/expanding cavities [9–11]. However, when the viscosity of a mixture increases, the particle velocity decreases [12]. Thus, solid particles either aggravate or relieve cavitation damage depending on the physical properties of the mixture [13]. Despite prior research on this topic, the effect of sediment particles on damage caused by cavitation erosion is still a poorly understood issue.

Sediment size and concentration are considered to be the crucial parameters that influence damage caused by cavitation erosion and abrasive wear. Researchers have attempted to discern a “harmful size”, and it is believed that damage increases with sizes around the harmful size, but there is variation in observed harmful sizes [14–16]. Yao [17] suggested that the harmful size ranges from 0.04mm to 0.14 mm for three types of steels. Satoh et al. [18] proposed that the range should be 0.08–0.17 mm. Yu [19] determined that sediment of 0.01 mm would enhance damage by 4–7 times. Furthermore, Zhong and Minemura [20] suggested that sediment sizes less than 1 mm rarely affect damage, but Xie et al. [21] considered that this is only true for sediment sizes less than 0.25 mm. In contrast, Wu and Gou [22] considered this minimum harmful size to be 0.048 mm.

Making observations during operation of the Chilime Hydro Electric Plant, Bajracharya et al. [23] determined that sediment of 0.2–0.5 mm was harmful for the middle and low water heads of the hydro station, sediment of 0.1–0.2 mm was harmful for the high water head of the hydro station. Wang [24] observed that sediment in the range of 0.05–0.5 mm were harmful. Sediment of 0.04–0.7 mm was harmful for the hydro turbines in the Yanguoxia hydro station.

Zheng [25] and Cheng [26] suggested that sediment can encourage

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damage in silt-laden water at low concentrations, but for high concentration, the sediment restrains the damage; Xing [27] obtained the critical concentration for this phenomenon. Padhy and Saini [28] concluded that the damage rate to a hydro turbine increases with the concentration of the silt irrespective of the silt size. Dunstan and Li [29] and Li [30] simulated the damage and predicted sizes of sediment that should reduce the damage. Hence, there remain disparate conclusions regarding the size and concentration of sediment for damage, which directly relates to the lifetime and safety of hydro-machinery and structures.

The present paper discusses the effects of adding sediment to water. Experiments were performed using a vibratory apparatus and a custom-made particle-moving device to identify the effects of the size (0.026–0.531 mm) and concentration (25–85 kg/m^3) of sediment for ASTM 1045 carbon steel.

2. Test apparatus and procedure

The experiments were conducted in the State Key Laboratory of Hydraulic Engineering Simulation and Safety at Tianjin University. The current study utilizes a vibratory apparatus and a particle-moving device. A diagram of the experimental apparatus is shown in Fig. 1(a).

A vibratory apparatus (KJ-1000; Wuxi Ultrasonic Electronic Equipment Co., Ltd.) is used to produce axial oscillations within each test specimen. The vibrations are generated by a magnetostrictive transducer driven by an electronic oscillator and a power amplifier. The vibratory frequency and amplitude are 19.6 ± 0.5 kHz and 50 µm, respectively. The corresponding output power is 1100 W. The temperature of the mixtures was controlled using cooling water system and maintained at 25 ± 3 °C.

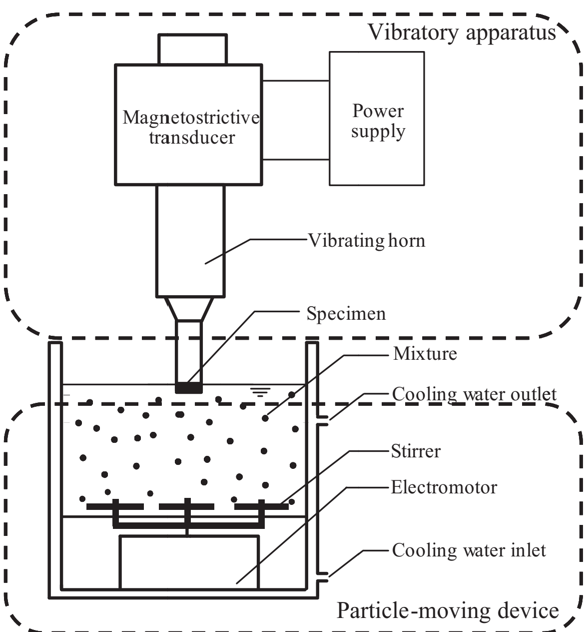
The custom-made particle-moving device keeps sediment moving on the surface of specimen to cause abrasion. The container for the sediment-containing water has three electromotor-propelled stirrers with a speed of 240 r/min, as shown in Fig. 1(b), that agitate the water and sediment in order to maintain a relatively flat water surface and a stable concentration of sediment on the water surface. To further avoid uneven distribution of sediment, the concentration of sediment is confirmed as the concentration of an area on the surface of the liquid around the specimen rather than the concentration of the mixture in the container.

Each test specimen has an exposed radius of 16 mm, and they are held below the horn tip and inserted to a depth of 12.5 ± 0.5 mm in the test liquid. The material of the specimen is ASTM 1045 carbon steel, and its density is 7.85 g/cm^3. The chemical composition of the specimen is shown in Table 1; the microstructure consists of ferrite (69.8%) and pearlite (30.2%).

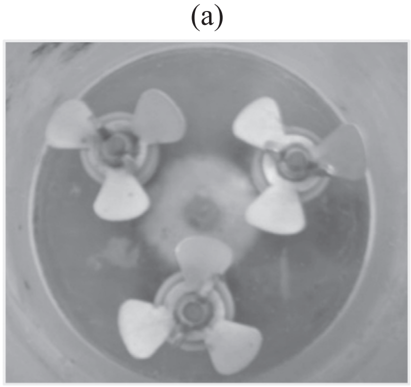
The mixture comprises distilled water and sediments. The sediments are composed primarily of feldspar and crystals, which have a Mohs hardness of 7 and a density of 2.65 g/cm^3. The sediment composition is shown in Table 2, and the sediment was classified into five classes, as shown in Table 3.

The experiment conforms to the standard test method for cavitation erosion by using a vibratory apparatus [31,32]. The mixture is prepared in advance. Sediment concentration is determined by the concentration at the center of liquid surface, instead of the concentration in the container. The test specimen is carefully cleaned, dried, and weighed on a balance with accuracy of 0.1 mg to determine its mass before the test and to determine the mass loss after test intervals of 30 min. The exposure time of each specimen is 240 min, and each case is repeated by three effective specimens, and the bias is in control of 5%.

The viscosity measurement utilizes a rotational viscometer (NDJ-8S; Shanghai Yueping Scientific Instrument Co., Ltd.). After testing each case, the viscosity of the sediment–water mixture is measured at temperatures of 10 °C, 25 °C, and 35 °C. Each case is repeated five times, and these results are averaged. The experimental cases include two groups, and details are shown in Table 4. The first group is selected to study the effect of a single size of sediment on cavitation damage; the objective of the second group is to study the effect of mixtures with two sediment sizes.



(a)



(b)

Fig. 1. (a) Schematic of test apparatus and (b) photograph of stirrers with three blades.

3. Results and discussion

In the experiments performed for this study, damage occurs as a result of cavitation in the distilled water or the combined erosion due to cavitation and abrasion in the mixtures with water and sediment. The damage is defined based on the mass loss of the specimen, which varies with exposure duration, particle size and sediment concentration.

Table 1
Chemical composition of specimen (balance is iron).

Chemical composition	*Mass* (%)
C	0.43
Cu	0.23
Mn	0.66
Ni	0.22
P	0.03
S	0.03
Si	0.24

Table 2
Sediment composition.

Composition	SiO_2	Fe	K_2O	Na_2O
Mass (%)	99.7	0.0062	0.0011	0.002

Table 3
Sediment sizes and classification.

Mean particle size d_{50}[a] (mm)	Classification
0.531	Coarse sediment
0.253	Medium sediment
0.063	Very fine sediment
0.042	Silt
0.026	Silt

[a] Mean particle size (d_{50}) is the value of the particle diameter at 50% in the cumulative distribution.

Table 4
Experimental cases.

No.	Size (mm)	Concentration (kg/m^3)	No.	Size (mm)	Concentration (kg/m^3)
1	0	0	18	0.026	40
2	0.026	25		0.043	10
3	0.026	50	19	0.253	25
4	0.026	85		0.531	25
5	0.043	25	20	0.253	10
6	0.043	50		0.063	40
7	0.043	85	21	0.026	25
8	0.063	25		0.253	25
9	0.063	50	22	0.026	25
10	0.063	85		0.531	25
11	0.253	25	23	0.026	40
12	0.253	50		0.253	10
13	0.253	85	24	0.026	10
14	0.531	25		0.253	40
15	0.531	50	25	0.026	10
16	0.531	85		0.063	40
17	0.026	25	26	0.026	40
	0.043	25		0.063	10

3.1. Surface damage analysis

Several photographs of the cavitation-only case of the tested surface for various exposure times are shown in Fig. 2(a). Some pits appear after 30 min on the experimental surface, and some cracks appear after 180 min. After 240 min, these cracks and pits are clearly visible on the surface. However, the deep pits and cracks only appear near the edge of the surface instead of covering the entire surface, which differ from the experimental results taken by Zhou [33], presumably owing to the different horn amplitude used. Based on the cavitation activity, the surface can be separated into three regions as shown in Fig. 2(b): the reduced-damage region, maximum-damage region, and damage-free region. The reduced-damage area, maximum-damage area, and damage-free area occupy approximately 62.5%, 25%, and 12.5% of the total cavitation surface, respectively. This is similar to the photographs taken by Diodati [34], especially in the damage-free region. This demonstrates that the liquid oscillations are relative to the specimen surface with a nonzero radial velocity [35].

Fig. 3 shows photographs of specimens exposed for 240 min in pure water and in mixtures with various sediment sizes at a concentration of 50 kg/m^3. The three regions of damage are visible in each case, and the craters and pits deepen and widen as the size of sediment increases.

3.2. Effects of time on damage

The cumulative mass losses of the specimens as functions of exposure time for the various sizes of sediments are shown in Fig. 4. The experimental results show that damage increases super-linearly with the exposure time for a given size and concentration. The mass loss due to cavitation of water without sediment is not the minimum value. Specifically, the mass losses caused by the two small sediment categories (0.026 mm and 0.043 mm) are less than the cavitation damage due to water without sediment.

After 240 min, the mass loss in the mixture with sediment of 0.026 mm is 6.2 mg (6.5%) less than the mass loss caused by water without sediment. Likewise, the sediment of 0.043 mm causes 1.6 mg (1.68%) less mass loss than water without sediment. However, the larger sediment causes more damage. The mass loss caused by sediment of 0.531 mm is 40.5 mg (42.45%) greater than that due to water without sediment. For sediment of 0.253 mm, the mass loss is 26.7 mg (27.9%) greater than that due to water without sediment.

3.3. Effects of sediment size on damage

Because smaller sediment can reduce the combined damage compared to cavitation-only damage, the effects of sediment size on the damage are considered and experiments are performed at concentrations of 25 kg/m^3, 50 kg/m^3, and 85 kg/m^3. Taking the damage at 240 min as an example, the relationships between mass loss and concentration and size of sediment are shown in Figs. 5 and 6 shows SEM photographs that have been magnified 1000 times in maximum-damage region of specimen surfaces in sediment-free water and water mixed with sediment of 0.026 mm and 0.253 mm at a concentration of 85 kg/m^3 after 240 min exposure.

The mass loss due to smaller sediment (sizes of 0.026 mm and 0.043 mm) decreases slightly as the concentration increases. In contrast, the bigger sediment (sizes of 0.063 mm, 0.253 mm, and 0.531 mm) causes more mass loss as the concentration increases. In Fig. 6, it can be seen that obvious marks of cavitation pit on the specimen surface and that some pits have been joined together to flake. The main failure mode is cavitation erosion [36]. Collapse of cavities destroys the structure of the specimen surface and causes material fatigue spalling, forming honey-comb pits. In addition, the photographs show that the specimen submerged in water mixed with sediment of 0.253 mm has been eroded most and the surface shows maximum roughness compared with that in Fig. 6(a) and (b). The specimen in water mixed with sediment of 0.026 mm has been eroded less than the specimen in the other two conditions for the surface in relatively smooth. The results shown in the photographs are consistent with the results of experiments. Sediment of 0.026 mm reduces the combined damage compared to cavitation-only damage and sediment of 0.253 mm enhances the combined damage. Therefore, the two groups of sediment have different influences on the combined damage of cavitation and abrasion, which is similar to the results obtained by Huang et al. [13] and Wu and Gou [22].

To identify a critical size, a dimensionless parameter (CES) is defined to represent the relationships between size and concentration of sediment and the combined damage of cavitation erosion and abrasive wear, providing a basis for choosing the two sediment sizes in the subsequent experiments. The CES is given as:

$$CES_{s,c}^{t} = \frac{WL_{s,c}^{t} - WL_{0}^{t}}{WL_{0}^{t}} \tag{1}$$

where WL is the mass loss caused by the sediment-water mixture; s, c, and t are sediment size, concentration, and exposure time, respectively; and WL_0 is the mass loss caused only by the cavitation of water. For example, $CES_{0.026,50}^{240}$ represents the damage parameter for the mixture with sediment of a size of 0.026 mm and a concentration of 50 kg/m^3

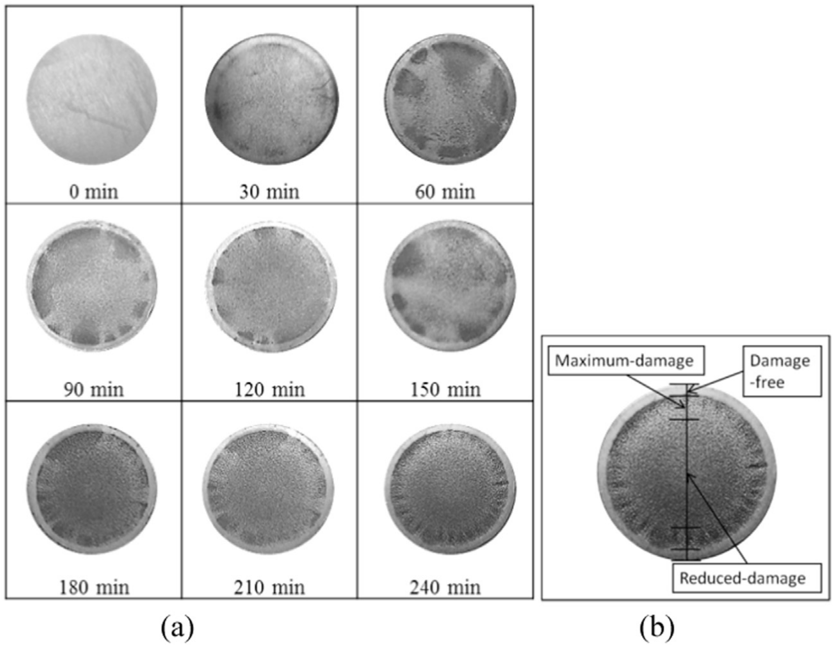


Fig. 2. Photographs of specimens; (a) photographs of specimens at several cumulative exposure times, (b) three regions of cavitation damage after 240 min exposure.

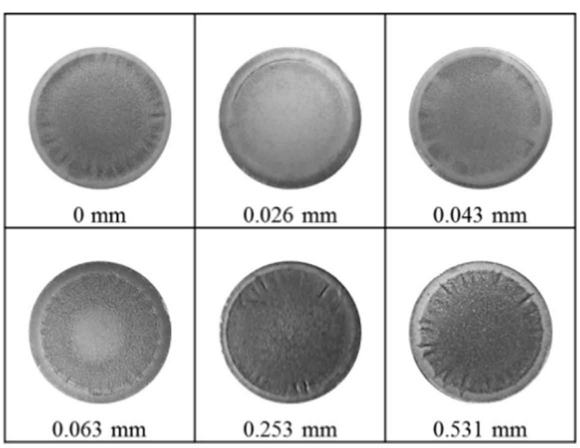


Fig. 3. Photographs of specimens exposed at 240 min in distilled water without or with sediments at a concentration of 50 kg/m^3.

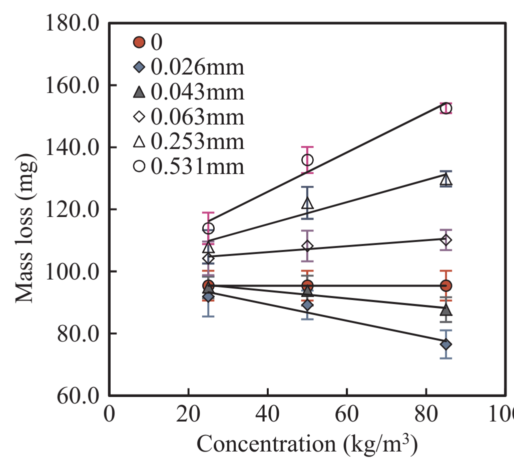


Fig. 5. Relationship between mass loss (with deviation) and sediments of various sizes and concentrations after 240 min.

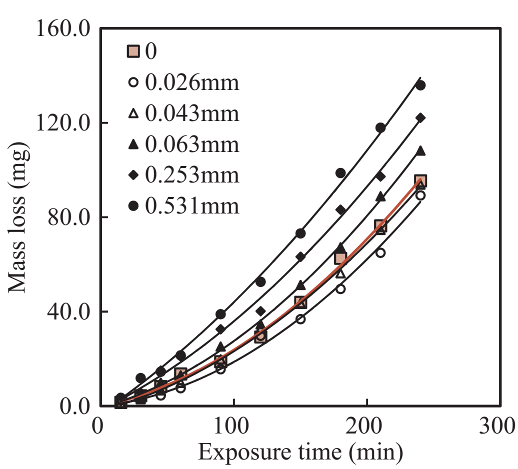


Fig. 4. Relationship between exposure time and cumulative mass loss in distilled water without sediment and with sediments at a concentration of 50 kg/m^3.

after 240 min; its value is −6.5%. As shown in Fig. 7, when CES is positive, the sediment enhances cavitation damage; whereas when CES is negative, the sediment inhibits cavitation damage. The critical size occurs when CES is equal to zero; based on these experiments, the critical size (D_c) is approximately 0.035–0.048 mm. Hence, for sediment sizes in the range of 0.035–0.048 mm, the combined damage is the same as cavitation-only damage.

3.4. Effects of sediment size on viscosity

The viscosity of the mixtures contributes to the effect of sediment on damage aggravation/relief. The relationships between the sediment size and the viscosity of the mixtures at various temperatures are illustrated in Fig. 8. The viscosity of the mixtures decreased as the temperature increased. Notably, the viscosity decreases as the sediment size increases, and the viscosity increases with the concentration, but only when this sediment is smaller than the critical size. However, the viscosity is essentially constant for all sediments bigger than the critical size and equivalent with that of pure water because the composition of larger sediment is mostly SiO_2 and the larger sediments are non-viscous particles.

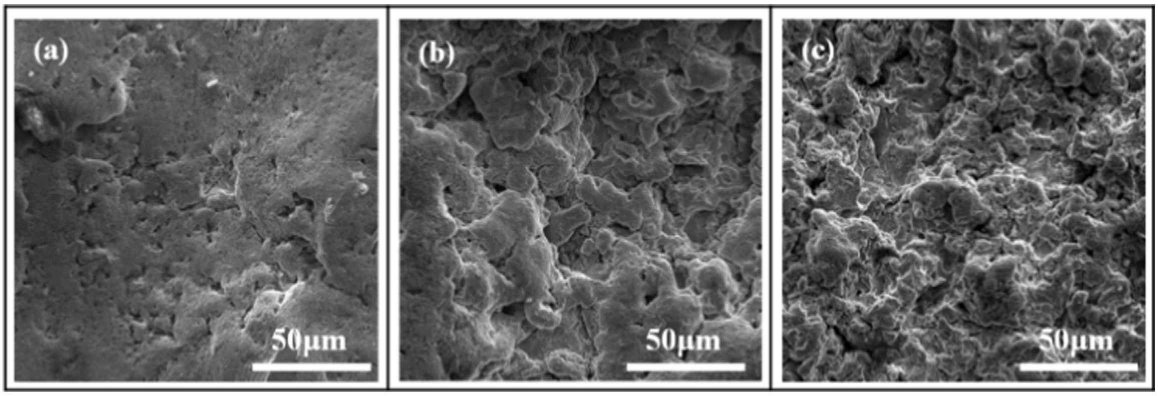


Fig. 6. SEM photographs of specimen surfaces in distilled water (b) and mixtures with sediments at a concentration of 85 kg/m^3 and various sizes (0.026 mm (a) and 0.253 mm (c)) at 240 min.

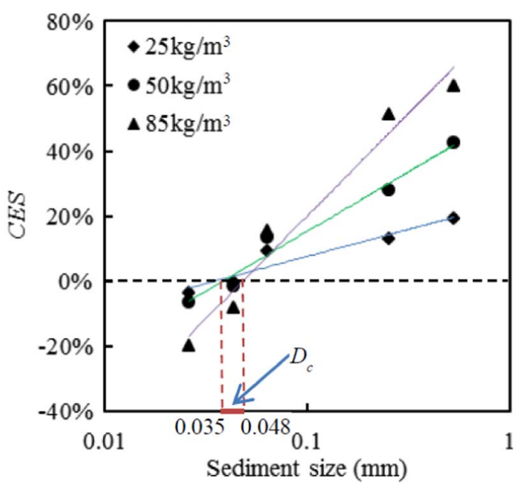


Fig. 7. Relationships between *CES* and sediment size for different concentrations after 240 min exposure.

The aforementioned correlation would explain the effects of sediment on inhibiting and enhancing cavitation damage. The viscosity of a mixture is the key to inhibiting damage [37]. For the mixtures with small sediment, the viscosity is higher than that of water alone, and the increased viscosity extends the duration of bubble collapse [38] and decreases particle velocity [12]. Therefore, higher viscosity inhibits cavitation damage. However, for mixtures with large sediment, the viscosity is the same as that of water, so it cannot affect cavitation damage; instead, the erosion damage is enhanced owing to abrasion because particles can be accelerated by the bubble expansion [10]. Hence, particle size is the primary cause of inhibiting or enhancing cavitation damage.

3.5. Effect of mixtures with two sediment sizes

More experiments are designed to further assess the effects of smaller sediment on damage. The experimental cases are decided according to the CES of a single size of sediment. In theory, at an exposure time of 240 min, the absolute value of the average CES of sediment of 0.026 mm (negative) is approximately one-quarter of the average CES of sediment of 0.531 mm (positive). Thus, mixing these sediments in a 4:1 ratio should result in a mixture with a CES of zero. Likewise, two sediment sizes with the same absolute values of CES (opposite in sign) should be mixed at concentrations with a 1:1 ratio to obtain a water-equivalent mixture. Therefore, experimental conditions are decided as a concentration of 50 kg/m^3 with ratios of 1:1, 1:4, and 4:1.

Fig. 9 shows the mass loss histories for water without sediment and two sediment sizes (0.026 mm and 0.043 mm) mixed in water at a concentration of 50 kg/m^3 with ratios of 4:1 and 1:1 (Cases 17 and 18); these two groups of sediment are smaller than the critical size. Fig. 10 shows photographs of specimens under these experimental conditions. The experimental results indicate that the concentration ratio has a relative effect on the damage caused by mixtures with two sediment sizes. The CESs of the 4:1 and 1:1 mixtures are −5% and −4.1%, respectively, and the mass losses are also less than that caused by distilled water.

The next set of experiments focuses on three sediment sizes that are all bigger than the critical size. Two cases (Cases 19 and 20) are considered: sediments of 0.531 mm and 0.253 mm with a 1:1 concentration ratio, and sediments of 0.253 mm and 0.063 mm with a 1:4 concentration ratio. As shown in Figs. 11 and 12, the experimental results demonstrate that the CES values of Cases 19 and 20 are 35.85% and 5.97%, respectively. The two mixtures cause more mass loss than water, and the damage caused by larger sediment is much more severe.

The next set of experiments (Cases 21 and 22) focuses on the effects of combining sediment bigger than D_c and sediment smaller than D_c. Two sizes that are bigger than D_c are considered (0.531 mm and 0.253 mm), and one size that is smaller than D_c is considered (0.026 mm). The two sediment sizes are mixed at a concentration of 50 kg/m^3 with a ratio of 1:1. The results are shown in Figs. 13 and 14. The results demonstrate that both experimental cases cause more damage than cavitation in distilled water, and the CESs for the mixed cases with large sediments of 0.253 mm and 0.531 mm are 12.7% and 22.1%, respectively. The results reveal that the inclusion of the small sediment partially inhibits erosion damage.

The next set of experiments (Cases 23 and 24) focuses on the effects of combining sediment bigger than D_c and sediment smaller than D_c in a concentration of 50 kg/m^3 with different ratios. Mixtures were prepared with two sediment sizes (0.026 mm and 0.253 mm) at relative concentrations of 1:4 and 4:1, because the CES of sediment of 0.026 mm with a 50 kg/m^3 concentration is −6.5% and the CES of sediment of 0.253 mm with a 50 kg/m^3 concentration is 28% at 240 min of exposure time. As shown in Figs. 15 and 16, the mass loss of the specimen with a relative concentration of 1:4 is substantially greater than that of the case with a 4:1 ratio. Both cases still result in more damage than the case of distilled water; however, these two cases result in slightly less damage than the mixture with only sediment of 0.253 mm. Thus, the experiment results demonstrate that the smaller size sediment can inhibit cavitation damage.

Finally, a set of experiments (Cases 25 and 26) is designed to determine if mixing a sufficient amount of small sediment with large sediment can reduce the resulting mass loss to be less than that of distilled water. The two sediment sizes are 0.026 mm ($< D_c$) and 0.063 mm ($> D_c$); these are mixed in relative concentrations of 1:4 and 4:1. The results are shown in Figs. 17 and 18.

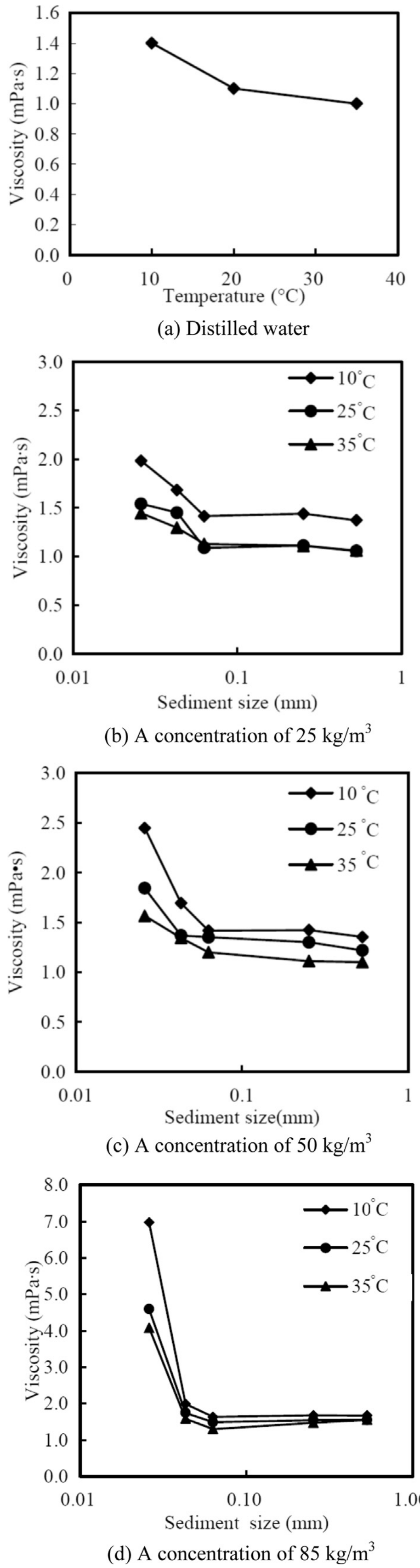


Fig. 8. Relationships between viscosity and sediment size in the mixtures with various concentrations at various temperatures.

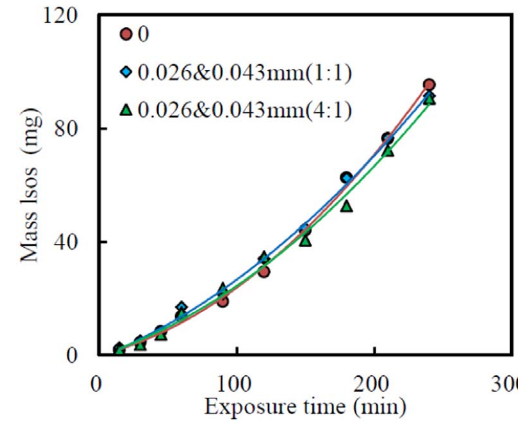


Fig. 9. Mass loss histories for the mixtures with two sediment sizes (0.026 mm and 0.043 mm) at a concentration of 50 kg/m^3 with different ratios (Cases 17 and 18).

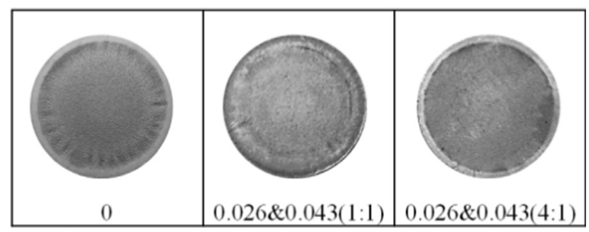


Fig. 10. Photographs of specimens in the mixtures with two sediment sizes (0.026 mm and 0.043 mm) at a concentration of 50 kg/m^3 with different ratios after 240 min (Cases 17 and 18).

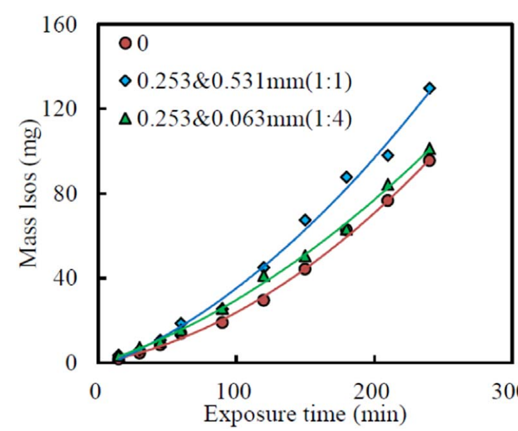


Fig. 11. Mass loss histories for the mixtures with two sediment sizes at different relative concentrations (Cases 19 and 20).

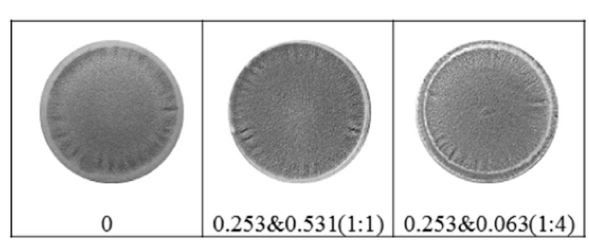


Fig. 12. Photographs of specimens in the mixtures with two sediment sizes at a concentration of 50 kg/m^3 with different ratios after 240 min (Cases 19 and 20).

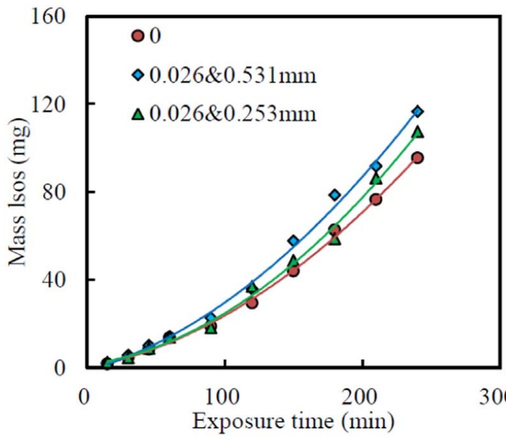


Fig. 13. Mass loss histories for the mixtures with two sediment sizes (0.026 mm & 0.253 mm and 0.026 mm & 0.531 mm) at a concentration of 50 kg/m^3 with a 1:1 ratio (Cases 21 and 22).

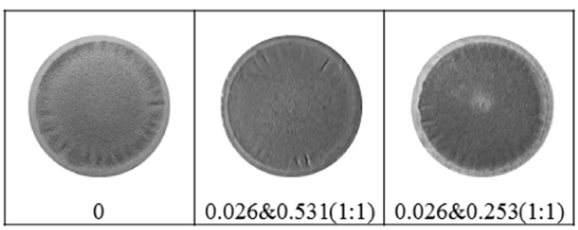


Fig. 14. Photographs of specimens in the mixtures with two sediment sizes (0.026 mm & 0.253 mm and 0.026 mm & 0.531 mm) at a concentration of 50 kg/m^3 with a 1:1 ratio after 240 min exposure (Cases 21 and 22).

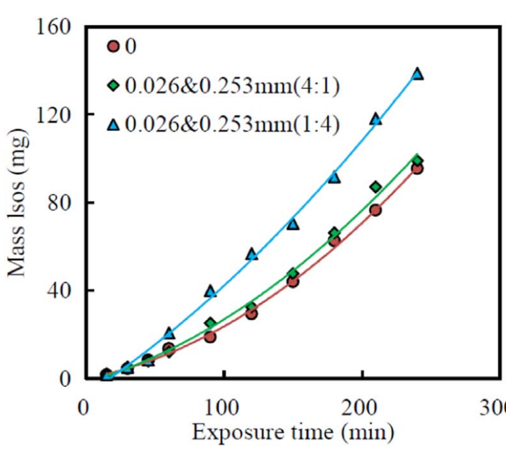


Fig. 15. Mass loss histories for the mixtures with two sediment sizes (0.026 mm and 0.253 mm) a concentration of 50 kg/m^3 with different ratios (1:4 and 4:1) (Cases 23 and 24).

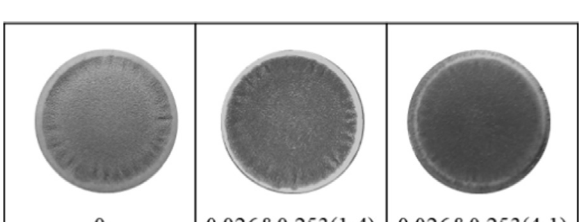


Fig. 16. Photographs of specimens in the mixtures with two sediment sizes (0.026 mm and 0.253 mm) at a concentration of 50 kg/m^3 with different ratios (1:4 and 4:1) after 240 min exposure (Cases 23 and 24).

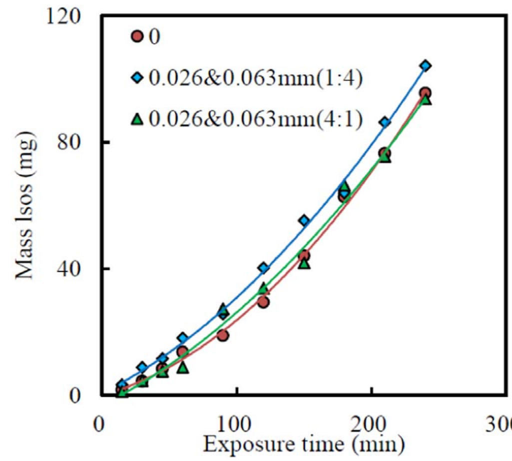


Fig. 17. Mass loss histories for the mixtures with two sediment sizes (0.026 mm and 0.063 mm) at a concentration of 50 kg/m^3 with different ratios (1:4 and 4:1) (Cases 25 and 26).

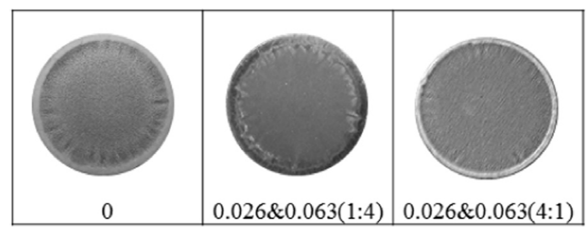


Fig. 18. Photographs of specimens in the mixtures with two sediment sizes (0.026 mm and 0.063 mm) at a concentration of 50 kg/m^3 with different ratios (1:4 and 4:1) after 240 min exposure (Cases 25 and 26).

Comparing these results, the mass loss for the mixture with a relative concentration of 1:4 is much greater than that for distilled water—the CES is 9.1%. However, the mass loss for the mixture with a relative concentration of 4:1 is close to the results for distilled water—the CES is −1.8%—which illustrates that the damage under this condition is the same as the cavitation damage caused by distilled water. For the Case 23 of a mixture with sediment of 0.026 mm and 0.253 mm with a relative concentration of 4:1, the CES value is 4%, which could be regard as the approximate damage in distilled water. These results demonstrate that this mixture is equivalent to the critical size of sediment for ASTM 1045 carbon steel. Hence, smaller sediment inhibits cavitation damage and larger sediment aggravates cavitation damage, which results from the interaction between sediment and cavities.

4. Conclusions

The damage caused by cavitation erosion and abrasive wear is a significant problem for hydro-machinery. Sediment plays a crucial role in the damage, and it can either inhibit or enhance the damage depending on its size. The findings are summarized as follows:

(1) For ASTM 1045 carbon steel at room temperature, the damage increases with exposure time (up to 240 min), for all combinations of sediment size (0.026–0.531mm) and concentration (25–85 kg/m^3).
(2) Based on the present study, the critical size of sediment (D_c) is approximately 0.035–0.048 mm. For sediment smaller than this size, the damage decreases as the concentration increases. In contrast, for sediment larger than this size, the damage increases as the concentration increases. Theoretically, the cavitation erosion and abrasive wear caused by a mixture with sediment of the critical size would be equivalent to the cavitation erosion caused by distilled

water.

(3) When sediment is smaller than the critical size, the viscosity is higher than that of water, and it increases as the size of sediment decreases or the concentration increases. This is evidence for the reduction of cavitation damage because increased viscosity extends the duration of bubble expansion and reduces the velocity of particles [38,39]. When sediment is bigger than the critical size, the viscosity is the same as that of distilled water, so the viscosity does not affect cavitation damage, but the velocity of sediment particles could be accelerated by bubble expansion [10], enhancing damage.

(4) Mixing small sediment into a mixture with large sediment reduces cavitation damage, which confirms that small sediment reduces cavitation erosion. It was shown that mixtures of multiple sizes of sediment can result in damage that is equivalent to that caused by distilled water—e.g., Case 23 (sediment mixed at sizes of 0.026 mm and 0.253 mm with a relative concentration of 4:1) and Case 26 (sediment mixed at size of 0.026 mm and 0.063 mm with a relative concentration of 4:1).

Further investigations are needed to determine the critical size, D_c, for different concentrations and other conditions.

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