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High-Performance Materials and Systems Research Program

An Evaluation of Materials for Repair of Erosion Damage in Hydraulic Structures

by James E. McDonald

Synopsis:

Erosion damage has been reported for approximately one half of the more than 600 hydraulic structures owned and operated by the U.S. Army Corps of Engineers. The causes of this erosion are about equally divided between cavitation and abrasion. In some cases this damage has been severe, requiring extensive repairs. Many different materials have been used in these repairs with varying degrees of success. Consequently, a study was initiated as part of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program to evaluate the cavitation resistance of a wide range of repair materials and protective coatings.

A venturi-type apparatus that produces moderate to severe cavitation was used to evaluate the cavitation resistance of approximately 80 materials. A ceramic-filled epoxy; a metal-filled, fiber-reinforced epoxy; and a polyurethane exhibited the best cavitation resistance. Cementitious-based materials generally performed rather poorly. Results of the laboratory tests are summarized herein.

BACKGROUND

Cavitation is the formation of bubbles or cavities in a liquid. In hydraulic structures, the liquid is water, and the cavities are filled with water vapor and air. The cavities form where the local pressure drops to a value that will cause the water to vaporize at the prevailing water temperature. Formation of these cavities is usually triggered by concrete surface irregularities that are subjected to high-velocity water flow. Cavitation bubbles will grow and travel with the flowing water to an area where the pressure field will cause collapse. When a bubble collapses or implodes close to or against a solid surface, an extremely high pressure is generated, which acts on an infinitesimal area of the surface for a very short time. A succession of these high-energy impacts will damage almost any solid material. Additional information on erosion of concrete in hydraulic structures is available in ACI 210 (1998).

Erosion damage has been reported to have affected more than one half of the 600 hydraulic structures owned and operated by the U.S. Army Corps of Engineers. In some cases this damage has been severe, requiring extensive repairs. Many different materials have been used in the repair of cavitation-damaged concrete with limited success. Consequently, a study was initiated as part of the Corps' REMR Research Program to evaluate the cavitation resistance of a wide range of repair materials and protective coatings.

CAVITATION TEST APPARATUS

A laboratory cavitation test apparatus was constructed by replacing a section of 305-mm-diam steel pipe with a venturi-type test cell, as shown in Figure 1.

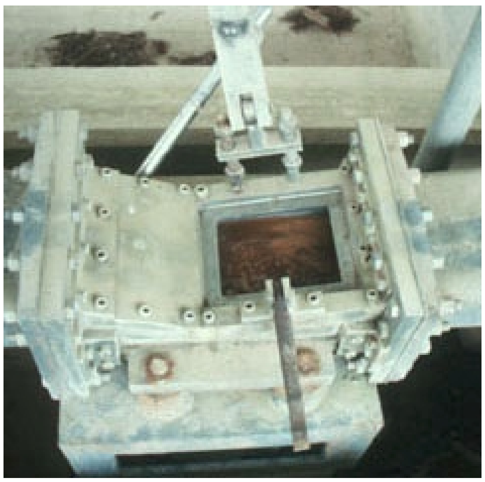

Figure 1. Open cavitation apparatus ready to receive a test specimen

A 120-kW electric motor drives a centrifugal pump at 1,750 rpm that draws water from a storage tank and produces a discharge velocity of approximately 35 m/sec through the venturi throat.

A series of calibration tests on the apparatus was necessary to ensure that vapor bubbles created during operation would collapse in the area directly under the relatively small test specimen (Figure 2).

The surface area of the test specimen exposed to the high-velocity flow and cavitation is approximately 150 cm^2.

The apparatus produces a moderate to slightly severe cavitation environment. Two hours exposure in this environment results in significant cavitation damage to conventional concrete with a compressive strength of 35 MPa and nominal 10-mm maximum size aggregate (Figure 3).

Volume loss during exposure to the cavitation environment was used to evaluate the cavitation resistance of a material.

Figure 2. Cavitation apparatus after installation of test specimen

MATERIALS

The materials evaluated were divided into two groups: repair materials and protective coatings. The repair materials were categorized as follows: conventional portland cement concrete, silica-fume concrete, latex-modified concrete, rapid-setting cementitious materials, fiber-reinforced concrete, and polymer mortar and concrete.

Three types of protective coatings were tested: neoprene, coal-tar, and polyurethane.

Figure 3. Conventional concrete after 2-hr exposure

TEST RESULTS

Each specimen was tested at approximately 28 days age. The specimen was placed in the test device and subjected to the cavitation environment for 2 hr, at which time the test was stopped and the specimen inspected. The volume of material lost during exposure to the cavitation environment was used to evaluate a material's cavitation resistance. Densities and volumes of the specimens calculated from dry mass and mass in water were used to determine the volume loss for appropriate time intervals.

Results of tests on the individual materials exhibited a wide range of cavitation resistance. Some materials exhibited significant volume losses after only 2 hr of exposure in the cavitation facility whereas other materials exhibited relatively low volume losses after 100 hr of exposure. Since the test duration was highly variable, a curve of best fit for individual tests was used to calculate the volume loss of each material after 50 hr of exposure. This procedure provided a rather simplified basis for comparing the relative performance of the various materials.

Cement-based materials

There was a significant correlation between volume loss and compressive strength for portland cement-based materials. An increase in compressive strength from 35 to 70 MPa resulted in a significant increase in cavitation resistance, while further increases in strength resulted in much smaller improvements (Figure 4).

The very high strength (>200 MPa) reactive powder mortar exhibited essentially the same cavitation resistance as the much lower strength (140 MPa) silica-fume mortars. For the range of materials tested, there was no obvious correlation between nominal maximum size of aggregate and cavitation resistance of cementitious-based materials (Figure 5).

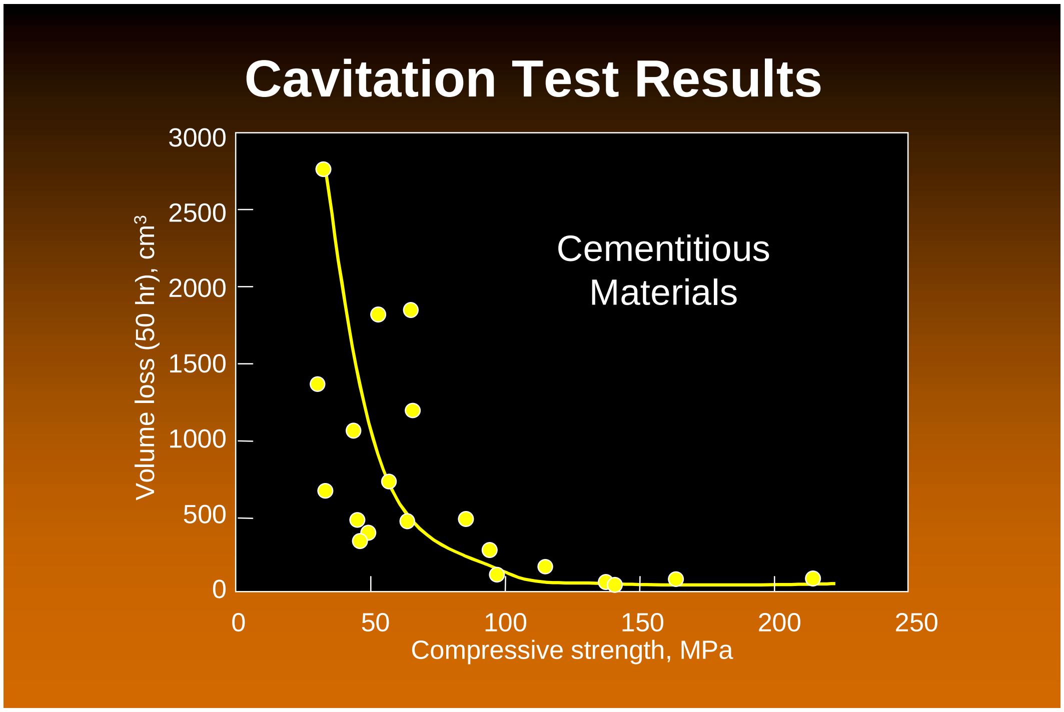

Figure 4. Volume loss versus compressive strength for cementitious-based materials

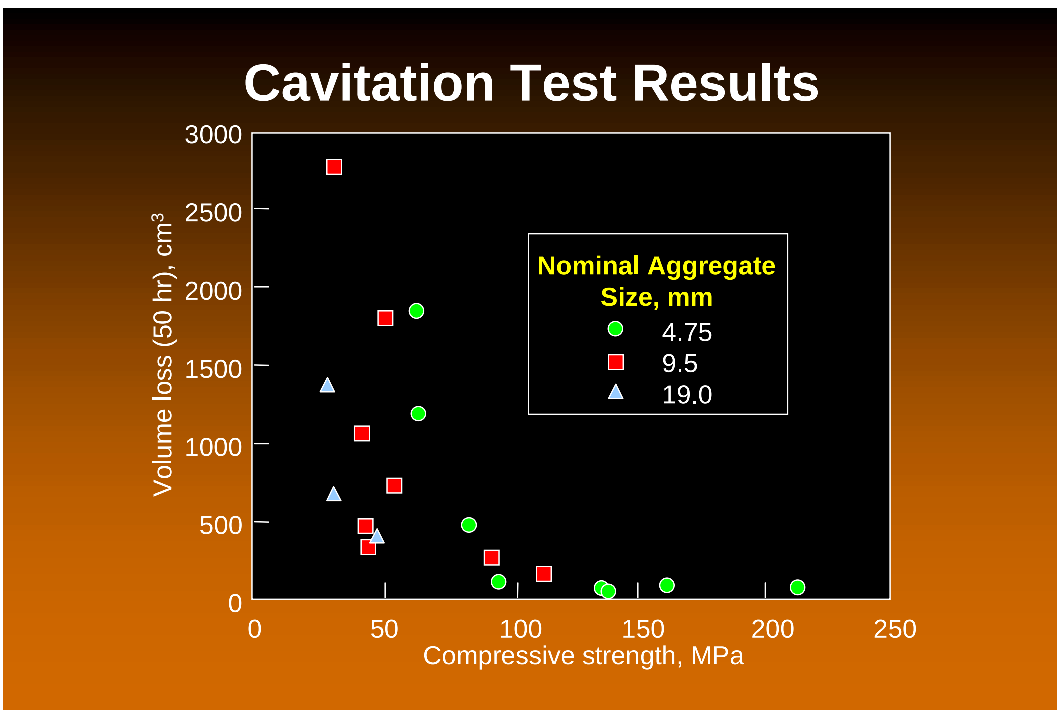

Figure 5. Effect of maximum size aggregate on cavitation resistance

The cavitation resistance of conventional concrete can be increased with the addition of silica fume and a high-range, water-reducing admixture. This increase is attributed to the denser pore structure and higher compressive strength typical of silica-fume concrete.

The addition of latex also increased the cavitation resistance of conventional concrete. For concrete mixtures with comparable compressive strengths, the volume loss of the latex-modified concrete was approximately 40 percent less than that for conventional concrete. This increased cavitation resistance is attributed to enhanced bond strength between the mortar and the coarse aggregate particles. The cavitation resistance of rapid-setting cementitious materials increased with increasing compressive strengths similar to that for conventional cementitious materials.

Concrete mixtures containing four types of steel fibers and two types of synthetic fibers (nylon and polypropylene) were tested to evaluate the cavitation resistance of fiber-reinforced concrete. The shape of the steel fibers varied primarily because of the different manufacturing processes. Fiber lengths ranged from 19 to 32 mm. Conventional concrete mixtures without fibers proportioned with three water-cement ratios (w/c 0.72, 0.54, and 0.41) and 19-mm nominal maximum size crushed limestone aggregate were used as control mixtures. Each control mixture was modified by adding fibers according to the manufacturer's recommendations and adjusting the aggregate quantities slightly to account for the volume change. As expected, the control and fiber-reinforced concrete mixtures generally exhibited increased cavitation resistance with increased compressive strength. However, it was somewhat surprising that, for a given w/c, the addition of fibers did not result in significant improvements in cavitation resistance (Figure 6). Also, with the exception of the 0.72 w/c mixtures, there was no significant difference in the cavitation resistance of the steel- and synthetic-fiber mixtures (Figure 7).

At 0.41 w/c, all of the fiber-reinforced mixtures exhibited a higher volume loss compared with the control mixture. The increase in volume loss for the four steel fiber-reinforced mixtures ranged from 2 to 60 percent with an average increase of 22 percent. However, excluding one type of fiber, the volume loss of the remaining steel fiber-reinforced mixtures averaged only 9 percent higher compared to the control. Both types of synthetic fibers exhibited similar cavitation resistance, with an average volume loss that was 50 percent higher than the comparable control. The volume loss of specimens containing nylon and polypropylene fibers averaged 23 percent higher compared with specimens containing steel fibers.

Additional tests were conducted on steel fiber-reinforced concrete mixtures proportioned with natural chert aggregate. At 0.41 w/c, all of the specimens containing steel fibers exhibited a higher volume loss compared with the control mixture. The increase in volume loss ranged from 3 to 78 percent, with an average increase of 26 percent. Overall, the volume loss for mixtures containing natural aggregate averaged 22 percent higher compared with the mixtures containing crushed aggregate.

One type of steel fibers was added to high-strength (0.18 w/c) silica-fume mortar mixtures proportioned with natural and bauxite fine aggregates. Overall, the addition of steel fibers had no significant effect on the cavitation resistance of these mortar mixtures. Adding fibers to the mixture proportioned with natural aggregate resulted in a 14 percent decrease in volume loss compared to a 13 percent increase in volume loss for the mixture proportioned with bauxite

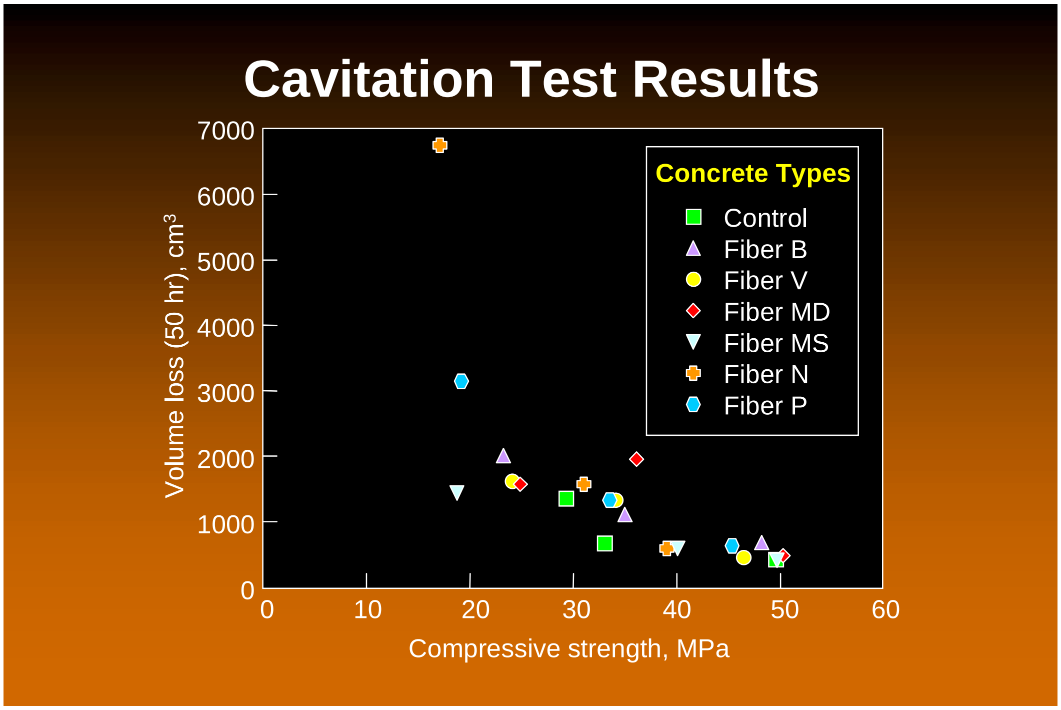

Figure 6. Cavitation resistance of fiber-reinforced concrete

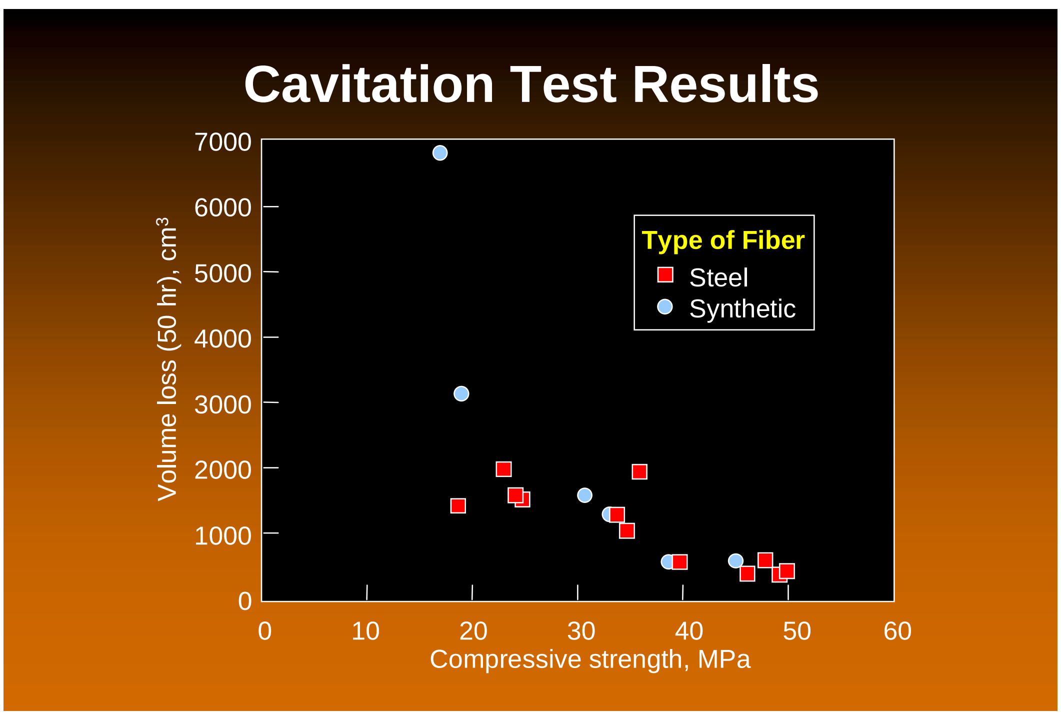

Figure 7. Effect of type of fiber on cavitation resistance

aggregate. Previous work with steel-fiber reinforced concrete subjected to underwater abrasion (Liu and McDonald 1981) showed an average increase in volume loss of 20 percent for given duration of exposure when fibers were used in concrete made with a given aggregate and given w/c.

Polymer-based materials

A wide variety of polymer-based materials were tested to determine resistance to cavitation. In contrast to the cementitious-based materials, there was no obvious correlation between compressive strength and volume loss for the polymer-based materials. Overall, the polymer-based materials exhibited significantly lower volume losses compared with the cementitious-based materials. Several of the polymer-based materials exhibited volume losses of less than 50 cm^3 after 80 to 100 hr exposure in the cavitation environment.

The epoxy-based repair materials were divided into four groups: flexible, high-modulus, low-modulus, and filled epoxies. Typical test results for the filled epoxy systems, categorized according to the type of filler, are shown in Figure 8. With the exception of one quartz-filled system, the calculated volume loss of all materials was less than 100 cm^3 after 50 hr exposure. The iron- and ceramic-filled epoxies exhibited the best cavitation resistance. The performance of these materials is compared with conventional concrete (50-MPa compressive strength) in Figure 9. Also, the ability of these two epoxy systems to bond to wet concrete surfaces makes them attractive for cavitation repairs, most of which are conducted in situations in which it is difficult, if not impossible, to obtain dry concrete surfaces during repairs.

In addition to epoxy, several other types of polymers were evaluated, including acrylics, polyesters, polyurethanes, and a styrenated polyester. With two exceptions, the calculated volume loss of all materials was less than 150 cm^3 after 50 hr of exposure (Figure 10). A polyurethane mortar exhibited the best cavitation resistance.

Protective coatings

The protective coatings tested were generally ineffective in preventing cavitation damage. This poor performance is attributed primarily to the design of the cavitation chamber, which resulted in high stresses at the leading edge of the test specimen. These stresses quickly eroded the concrete at the edge of the specimen and, in most cases, caused the coating to peel off without significant damage to the coating itself.

DISCUSSION

In general, the cementitious-based materials exhibited poor cavitation resistance. While the cavitation resistance of conventional concrete was improved in some cases with the addition of latex, silica fume, reactive powder, and fiber reinforcement, volume losses for most of these materials were significantly higher than many of the polymer-based materials (Figure 11). Of the more than 100 materials tested, the calculated volume loss was less than 100 cm^3 after 50 hr of

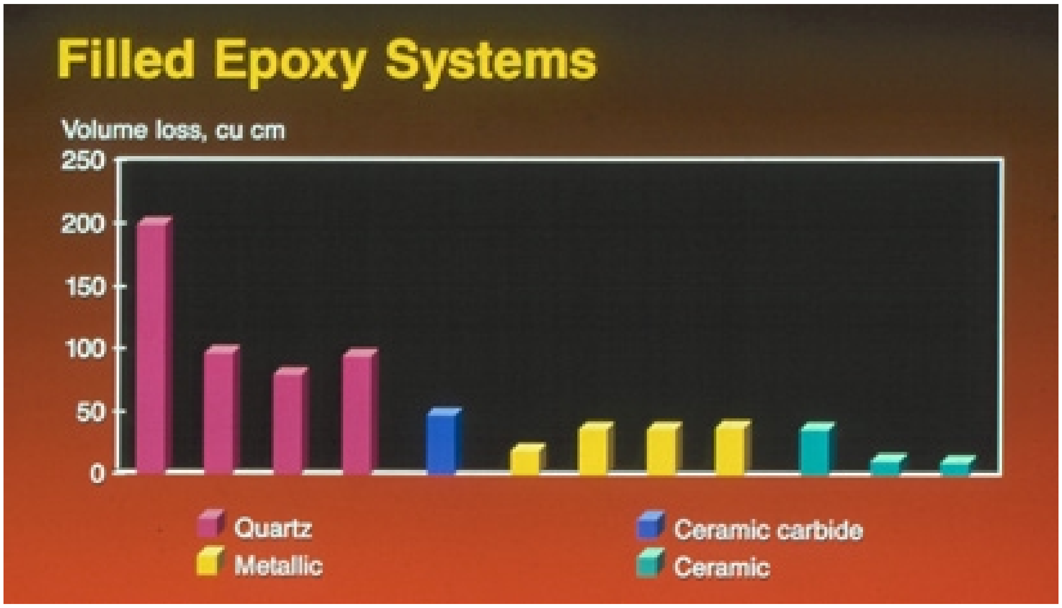

Figure 8. Volume loss of filled epoxy systems

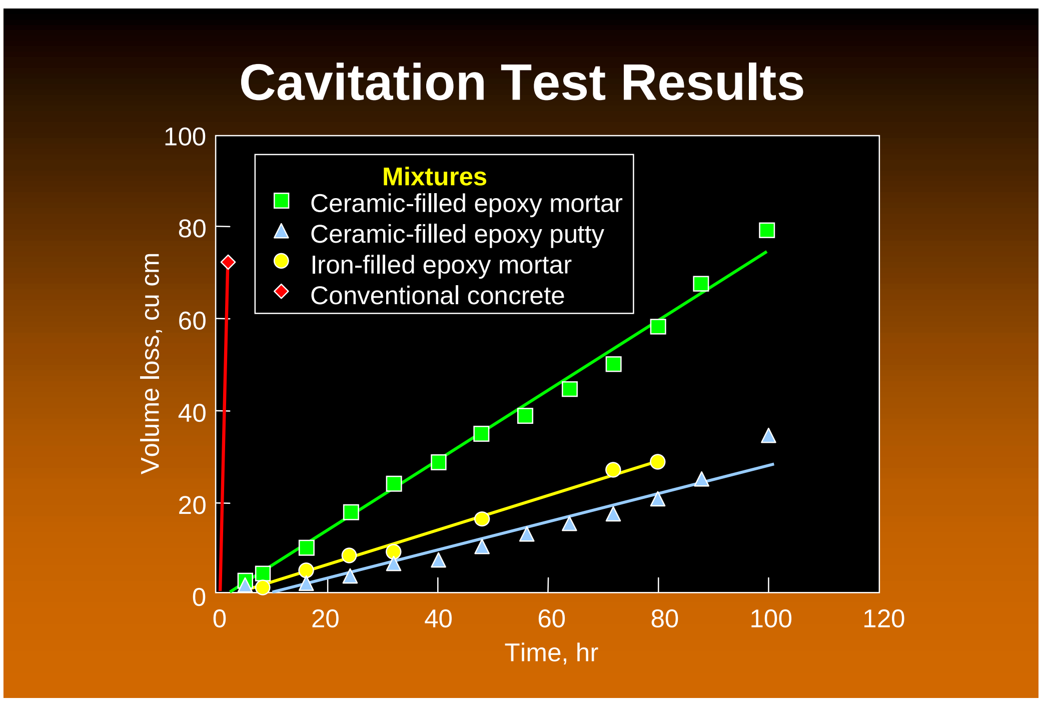

Figure 9. Cavitation resistance of filled epoxy systems compared to conventional concrete

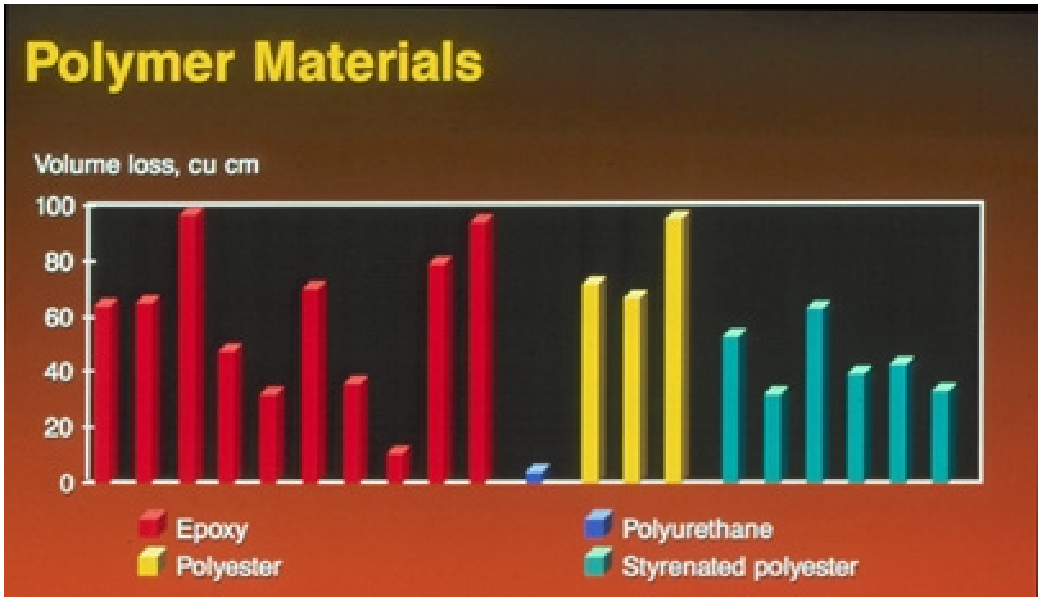

Figure 10. Volume loss of selected polymer-based materials

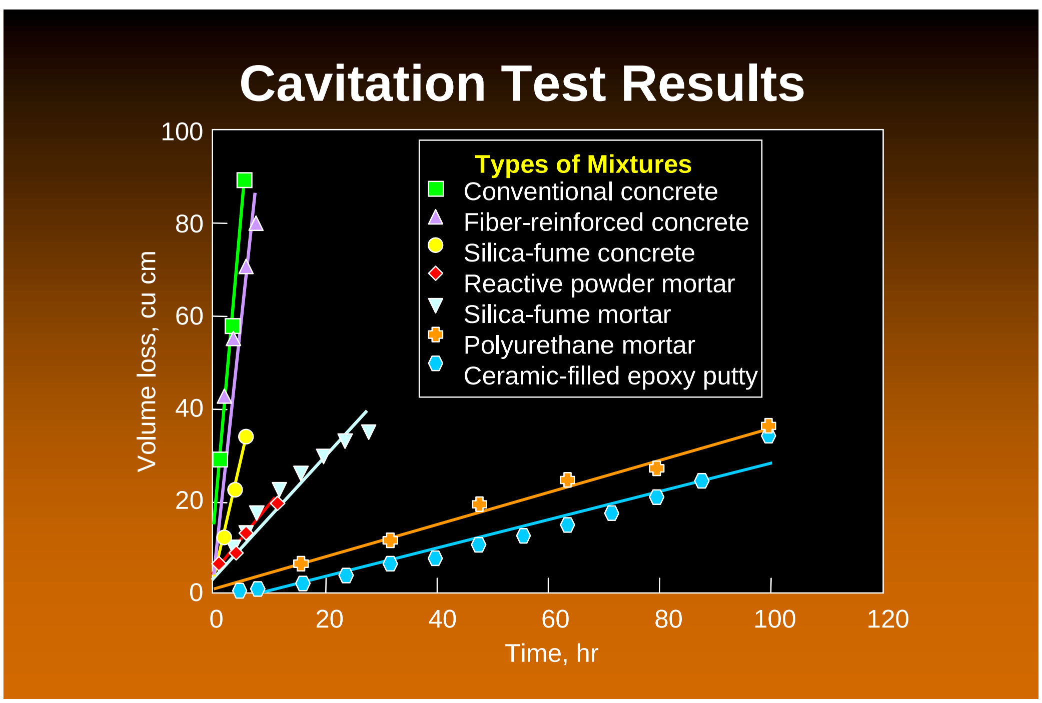

Figure 11. Relative cavitation resistance of selected types of repair materials

exposure for about 20 polymer-based materials compared with only 6 very high-strength cementitious-based materials.

While several materials are available to reduce cavitation damage, a fundamental and certain approach for minimizing cavitation damage is to use appropriate hydraulic design and construction practices (ACI 210R).

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ABOUT THE AUTHOR

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