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Development of Specialized Sulfur Concretes

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By William C. McBee and Thomas A. Sullivan

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DEVELOPMENT OF SPECIALIZED SULFUR CONCRETES

by

William C. McBee[1] and Thomas A. Sullivan[2]

ABSTRACT

Specialized sulfur concretes were developed by the Federal Bureau of Mines as a result of research for the beneficial utilization of sulfur in construction materials. Materials were developed for use in acid and salt corrosive environments where portland cement concrete has been found to deteriorate. Because the mineral aggregates also come into contact with the corrosive media, concretes were developed utilizing both limestone and quartz aggregates. The sulfur binder used with both aggregates was modified by reaction with 5 pct dicyclopentadiene to improve product durability. Sulfur quartz aggregate concrete was found to have moderately high strength characteristics (6,000 psi compressive) and was extremely resistant to chemical attack by both acid and salt solutions. Sulfur limestone aggregate concrete exhibited very high strength characteristics (9,000 psi compressive) and was extremely resistant to chemical attack of salt solutions. Both types of concretes maintained their strength and integrity after long-term testing in acid and salt solutions and exhibited considerable resistance to damage by the action of freezing and thawing. Potential uses include leach tanks, electrolytic cells, thickeners, bridge decking, industrial flooring, pipe, and tile.

INTRODUCTION

The Federal Bureau of Mines in 1972 initiated research to develop new, beneficial uses for sulfur to take advantage of a projected surplus of the material in the 1980's (43)[3]. Part of the research was to develop and evaluate concrete materials that were made by using sulfur to bind the aggregate together instead of portland cement. The potential use of sulfur as a cementing agent is not new; 17th century examples of using sulfur to anchor metal to stone still exist in Latin American (35). At the end of World War I, a sulfur surplus existed in this country, and this stimulated research into new uses

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[3] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

for sulfur. In 1921, Bacon and Davis, reported on projected uses of sulfur in the construction industry (2). They found that although many additives had been proposed to modify sulfur and enhance its properties, most of these were unsuitable. They developed an acid-resistant mortar containing 40 pct sulfur and 60 pct sand for use in the chemical industry. In the early 1930's, Duecker found that the sulfur mortars grew or expanded on thermal cycling with a loss of flexural strength and subsequent failure of the mortar (16). He found that sulfur that was reacted with an olefin polysulfide, Thiokol, and then mixed with sand produced a mortar that was not seriously affected by thermal cycling. This use of an additive to modify the properties of the sulfur used in preparing mortars led to industrial acceptance of the materials. More recent research into sulfur utilization in construction materials was initiated by Dale and Ludwig, starting in the early 1960's (9-13). In 1970, Crow and Bates reported on development of high-strength sulfur-basalt concretes (7). Since then, as the potential surplus of sulfur became more evident, research into new uses for sulfur in construction materials has expanded greatly (3-6, 8, 12-16, 17-24, 26-46). Sulfur concretes were developed with strength properties equivalent or superior to those of portland concretes. However, many of these were found to be vulnerable to destruction on exposure to weathering, thermal cycling, or alternately wet-dry conditions. The problem was similar to that encountered with the sulfur mortars before Duecker modified the sulfur by reaction with an additive. The probable reason for the susceptibility of sulfur concretes to failure is the allotropic transformation sulfur undergoes when cooled from the melt. Solid sulfur transforms upon cooling below 95.5° C from the monoclinic (S_b) to the orthorhombic (S_a) crystalline form, which is more dense and occupies less volume, resulting in a highly stressed product. Thus, any process that will stress-relieve the material, such as thermal cycling, will result in disintegration of the concrete. The authors found in previous research that reacting sulfur with 5 pct dicyclopentadiene before mixing with aggregates gave durable sulfur concrete products (41). The sulfur in these products did not revert to S_a on cooling and was not sufficiently plasticized to deleteriously affect their compressive strengths. Sulfur reacted with dicyclopentadiene was shown to form polymeric polysulfides and free unreacted sulfur composed of S_b and liquid sulfur (S_8), (5, 8). After 18 months of storage at ambient temperatures, Currell (8) found no crystallization of these products to S_a, and there was less recrystallization of S_8 to S_b in sulfur reacted with 5 pct dicyclopentadiene than with 10 pct dicyclopentadiene. Diehl reported on the use of dicyclopentadiene as a modifier of sulfur to be used as a binder in preparing sulfur concretes (15) and also found that 5 pct dicyclopentadiene was the optimum to obtain the desired sulfur modification. Vroom has reported on the preparation of sulfur concretes in which the sulfur was modified with a proprietary additive (45). Dicyclopentadiene was chosen as the modifier for this work on the basis of low cost, commercial availability, and properties of the modified sulfur.

This Bureau of Mines report concerns the development and testing of specialized sulfur concretes designed for use in environments where resistance to corrosion by acid or salt solutions is desired. Previous research had shown that the type of aggregate used in making sulfur concretes had an effect on the properties and performance of the material. It was found that basic aggregates such as limestone formed higher strength materials, possibly owing to the formation of a chemical bond between the sulfur and the aggregate. With acidic aggregates, composed primarily of silica, lower strengths were developed, and there was less evidence of chemical bonding between the sulfur and aggregate. Because the mineral aggregates also come into contact with the corrosive media, the present study was designed utilizing two different homogeneous aggregates, limestone and quartz, to develop materials for testing in the various corrosive environments. The concretes were characterized for mechanical properties, freeze-thaw durability, and corrosion resistance in acid and salt solutions.

EXPERIMENTAL WORK

Materials

Commercial-grade flake sulfur (99.9 pct minimum) from a secondary source was used. A technical grade of dicyclopentadiene was used to modify the sulfur.

Two homogenous aggregate materials were investigated. One was composed of equal portions of minus 1/2-inch silica rock and silica sand. The rock was essentially 99 pct quartz, and the sand was 95 pct quartz. The second aggregate was equal portions of minus 1/2-inch limestone rock and minus 1/8-inch limestone sand. The limestone was principally calcite with minor amounts of dolomite, quartz, and feldspar. Sand was prepared by crushing the limestone rock.

Modified-Sulfur Preparation

Modified sulfur was prepared by reacting sulfur with 5 wt-pct dicyclopentadiene in a closed, heated vessel equipped with a stirrer. The reactor is shown in figure 1. Batches of 315 pounds were prepared by adding 300 pounds of sulfur to the reactor, stabilizing the temperature at 120° C with virgorous stirring, and adding the dicyclopentadiene in small increments so that the reaction temperature did not exceed 130° C. If the dicyclopentadiene is added too rapidly, the reaction temperatures will be in excess of 140° C, which will render the product stiff and difficult to work. After completing the dicyclopentadiene addition, the reactor temperature was raised to 130° C and maintained for 10 hours to insure complete reaction. Normal safety precautions were observed in handling the dicyclopentadiene because it is flammable and has been reported to be slightly toxic (25). On completion of the reaction, the modified sulfur was drained from the reactor and either used immediately to prepare sulfur concrete or cast into solid billets that could then be remelted as needed. The modified sulfur product is practically odorless and can be stored indefinitely. Modified sulfur will be designated in this paper by the letter M after its concentration.

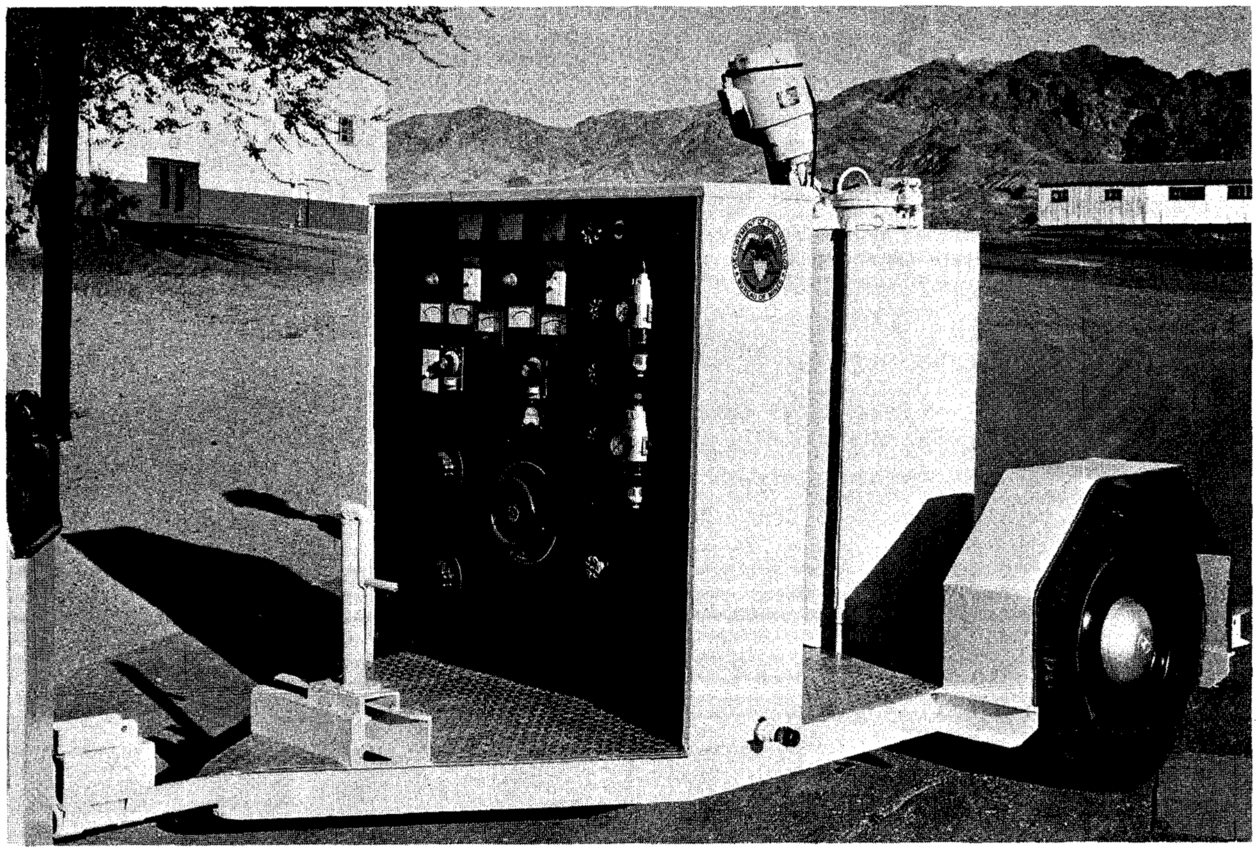

FIGURE 1. - Equipment for preparing modified sulfur.

Sulfur Concrete Mix Design

Since there are no standard mix design methods for sulfur concrete, all mixtures were designed to optimize compressive strength. Sulfur concentration was varied with a given aggregate mixture until maximum compressive strength properties were obtained. At the optimum strength, it was generally found that maximum workability and minimum void levels were obtained. Generally, blends of equal portions of fine and coarse aggregate, containing approximately 25 pct voids, produced suitable aggregate blends. Normally, between 22 and 26 pct sulfur was required to fill the voids and produce maximum strength.

Mixing of the Materials and Test Samples Preparation

A standard procedure was developed for preparing specimens for strength, corrosion, and freeze-thaw testing. This was necessary to insure sound samples for comparing the properties of various sulfur-concrete mixtures. Sulfur concrete cast into standard concrete compression sample molds develops a porous shrinkage area in the top of the sample even with good tamping and refilling of the mold as it cools. The following procedure was used to obtain sound samples and minimize differences between samples.

Standard cylindrical concrete compression molds 3 by 6 inches and 6 by 12 inches were fitted with 3-inch extensions on top of the molds. Sulfur concretes were prepared in batches of approximately 80 pounds by mixing together aggregate (160° to 170° C) and either sulfur or modified sulfur (140° C) in a heated mixer bowl (150° C) for 2 min with a Triumph[4] mixer and then tamping into the molds. The molds and tamper were preheated to 120° C. The tamper was a 3/4-inch steel rod with a hemispherical tip. After tamping, the samples were cooled to room temperature, removed from the molds, and the top 3 inches were cut off and discarded. The compression samples were capped with a standard sulfur capping compound before testing. All test measurement results are for samples aged 1 day unless otherwise specified.

Sulfur concrete beam samples were cast in a similar manner. Beams 3 by 3 by 14 inches and 3 by 4 by 16 inches were prepared in preheated vertical molds with tamping. Molds 3 inches longer than the desired sample length were used, and the top 3 inches were cut off before testing. Larger beam samples, 6 by 6 by 30 inches, were cast into horizontal molds with tamping. Some of the larger beams were cast in one pouring, others were cast in four lifts, allowing the concrete to solidify between lifts. On the larger beam samples, additional material was added to the top of the beam surface as shrinkage occurred to obtain a level surface. The mixer and the various molds used in preparing the test samples are shown in figure 2.

Testing of Sulfur Concretes

Compressive Strength

Measurements of the compressive strengths of sulfur concretes prepared with both types of aggregate materials were made in accordance with ASTM Method C 39-72, "Compressive Strengths of Cylindrical Concrete Specimens" (1, pp. 25-27). Most measurements were made using 3- by 6-inch, capped, cylindrical specimens; however, some 6- by 12-inch samples were also tested. All samples tested after exposure to salt or acid corrosion were rinsed with distilled water and air-dried for 24 hours before testing.

Tensile Strength (Indirect)

Concrete cylindrical specimens (3 by 6 inches) were used to determine tensile strength by ASTM Method C 496-71, "Splitting Tensile Strength of Cylindrical Concrete Specimens" (1, pp. 308-313).

Flexural Strength

Measurements of the flexural strength of the sulfur concretes were made on bars of the materials measuring 3 by 3 by 12 inches or 6 by 6 by 36 inches. Testing was in accordance with ASTM Method C 78-75, "Flexural Strength of Concrete (Using Single Beam With Third-Point Loading)" (1, pp. 38-40).

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[4] Reference to specific brands is made for identification only and does not imply endorsement of the Bureau of Mines.

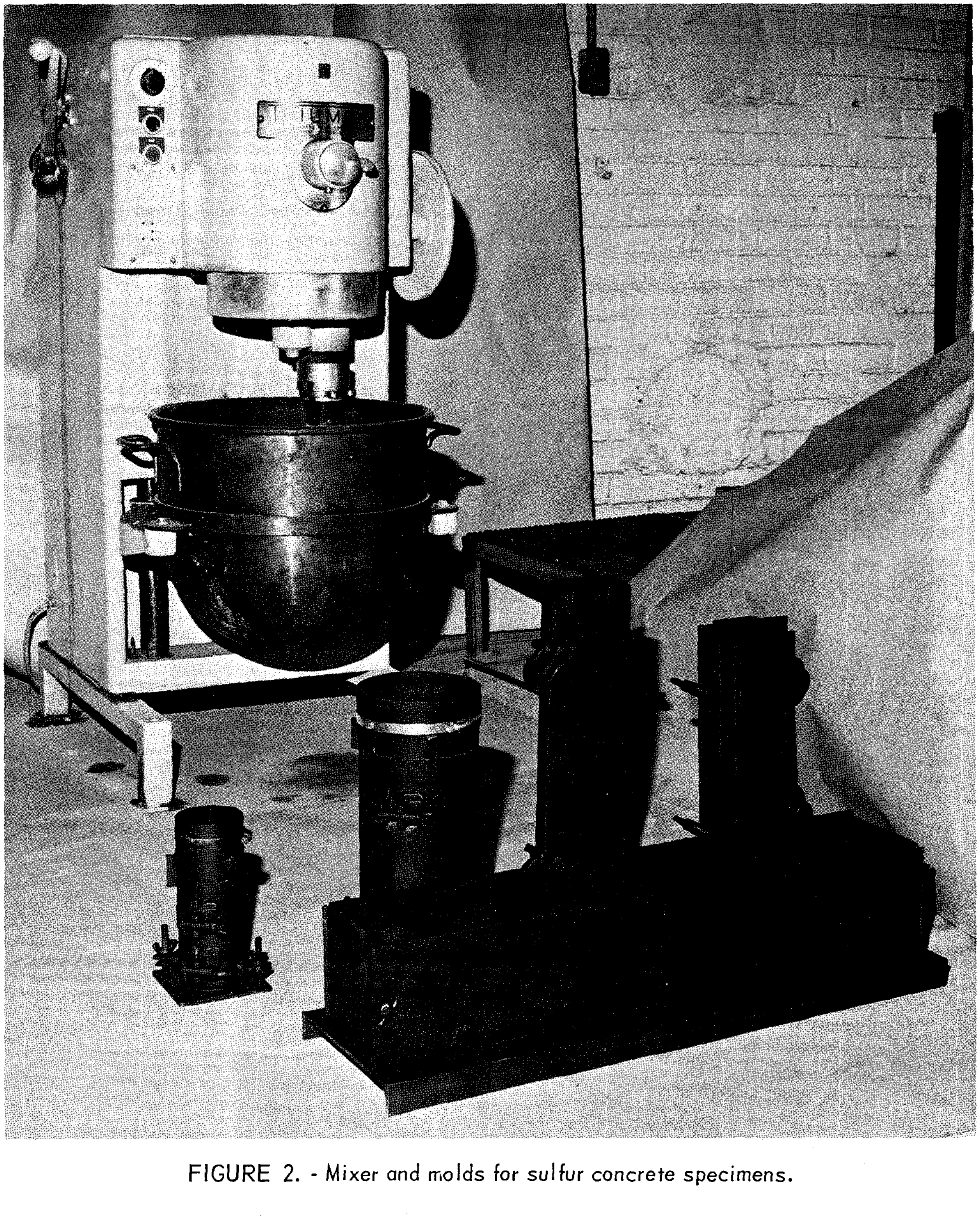

FIGURE 2. - Mixer and molds for sulfur concrete specimens.

Resistance of Sulfur Concrete to Freezing and Thawing

Durability of sulfur concretes to freezing and thawing conditions was evaluated by ASTM Method C 666-76. "Resistance of Concrete to Rapid Freezing and Thawing" (1, pp. 371-375). Concrete prisms 3 by 3 by 12 inches in size were cycled between 0° and 40° F six times per day by alternately freezing and thawing in water. Testing duration was 300 cycles.

Acid Corrosion Resistance

Sulfur concrete designed for use in acid environments was tested for its durability by two methods. The first method consisted of immersing test cylinders and bars of the concrete in water and in 1.8, 8.8, and 17.0 wt-pct sulfuric acid solutions. Test duration was 1 year with one set of test specimens removed after each 2-month increment of exposure to determine weight change, specific gravity, compressive strength, flexural strength, and splitting tensile strength. In addition, the samples were visually examined for any evidence of erosion, swelling, or disintegration. The acid-resistant sulfur concretes tested were composed of silica aggregate and four sulfur binder levels: 24 and 26 pct sulfur and 22 and 24 pct modified sulfur. Determination of the strength values at 2-month intervals required one hundred ninety-two 3- by 6-inch cylinders for compression and tensile strength determinations and ninety-six 3- by 12-inch bars for flexural strength measurements. Figure 3 shows the samples prior to testing.

The second method of evaluating the acid-resistant sulfur concrete was to use it in constructing a tank similar to those used in electrowinning copper from a sulfuric acid electrolyte. Resistance to corrosion and erosion was evaluated with a circulating acid solution. Materials used in construction were silica aggregate bonded with 22 wt-pct modified sulfur. The cell was 3-1/2 feet wide by 3-1/2 feet high by 6-1/2 feet long; this is approximately the same width and height as for a normal copper cell, but only one-half of the length. The cell had a total capacity of 400 gal of solution. Because of the limited capacity in the laboratory for heating aggregate, the cell was constructed in nine segments on separate days. First, a 4-inch-thick unreinforced floor was cast, and then four wall sections, which were 5 inches thick. The wall sections were reinforced with No. 4 reinforcing steel set on 1-foot centers. Corner sections were then poured to join the four wall sections. Bonding of the joints of the cell was through direct sulfur-concrete contact. Sulfur-concrete mixtures were prepared by mixing liquid modified sulfur and hot aggregate in a heated mortar mixer for 2 min at 265° to 280° F. The concrete was poured into regular plywood forms and compacted by hand tamping and external vibration on the forms. On completion, 270 gal of water was placed in the cell, and a circulating pump was installed to circulate the solution in one end of the cell and out the other at a flow rate of 1.7 gpm. Sulfuric acid was added at regular intervals over a 3-month period to increase the acid concentration in the cell to 8.8 wt-pct. The completed cell with acid solution circulating is shown in figure 4.

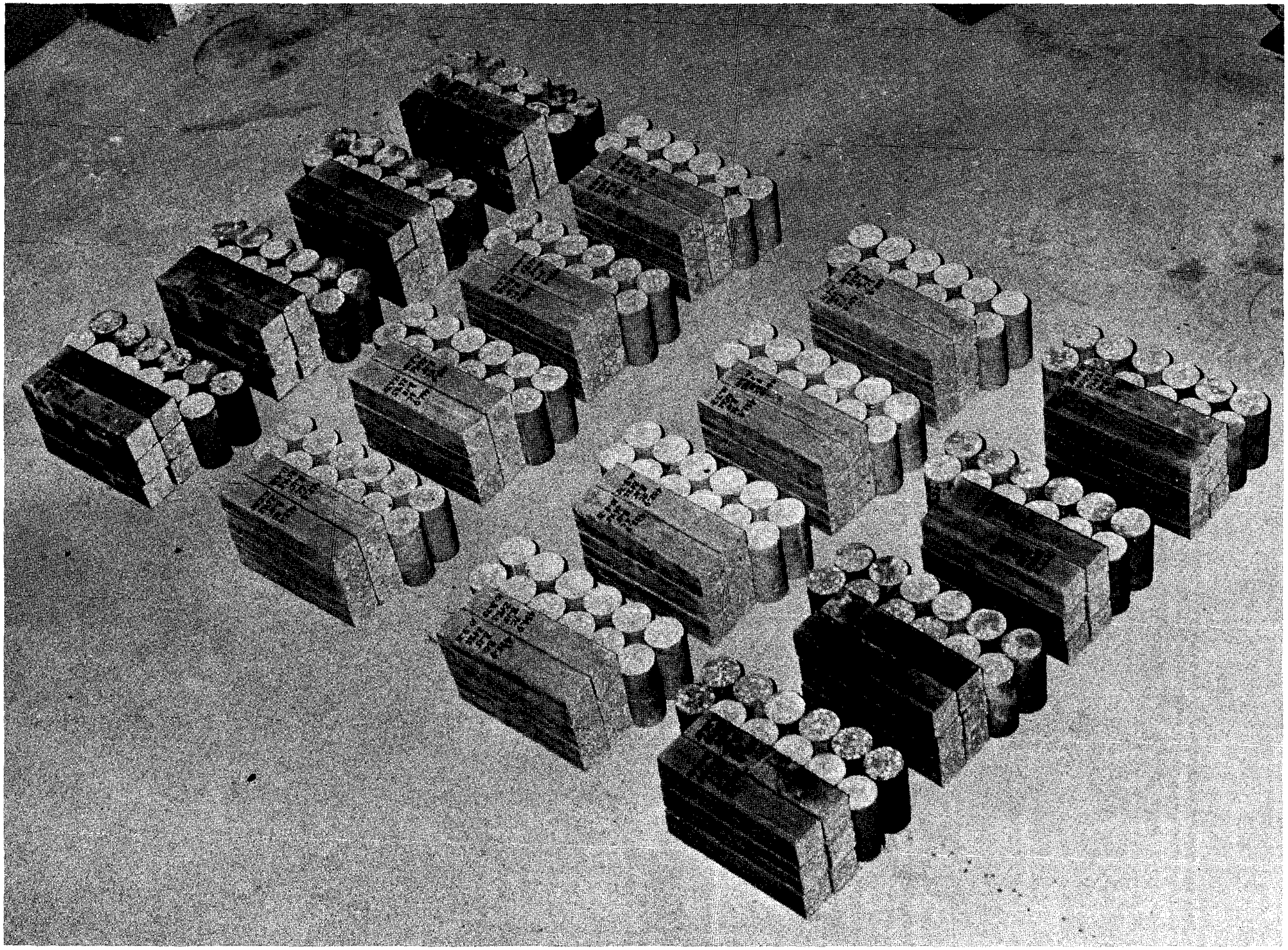

FIGURE 3. - Specimens for corrosion testing.

FIGURE 4. - Sulfur concrete electrolytic cell.

Salt Corrosion Resistance

Both specialized concretes were tested for resistance to salt corrosion by immersing cylinders and bars of the concretes in 5 wt-pct solutions of $CaCl_2$, NaCl, and Na_2SO_4 and determining any loss in weight of the specimens over a 1-year period. The specimens were similar to those used in the acid-corrosion-resistance testing. Every 3 months, the specimens were removed from the solutions, rinsed, and dried. The samples were weighed to determine any change in weight from corrosion, absorption, or disintegration. Surface examinations were made to check for visible signs of cracking or sloughing of the material. At the conclusion of the 1-year test period, the samples were used to determine their residual strengths after immersion in the salt solutions.

Four levels of sulfur binders were used with each aggregate. Silica aggregates were mixed with 24 and 26 wt-pct sulfur and 22 and 24 wt-pct modified sulfur. Limestone aggregates were mixed with 22 and 24 wt-pct sulfur and 21 and 23 wt-pct modified sulfur. A total of 82 sample cylinders and bars were tested.

RESULTS

Sulfur Concrete Mix Design

The size gradations of the aggregates used are shown in figure 5. Physical properties of the aggregates are presented in table 1.

TABLE 1. - Physical properties of aggregates

Aggregate	Bulk sp gr	Voids, pct	Unit weight, pcf
Silica........	2.620	25.4	121.9
Limestone.....	2.703	25.5	125.6

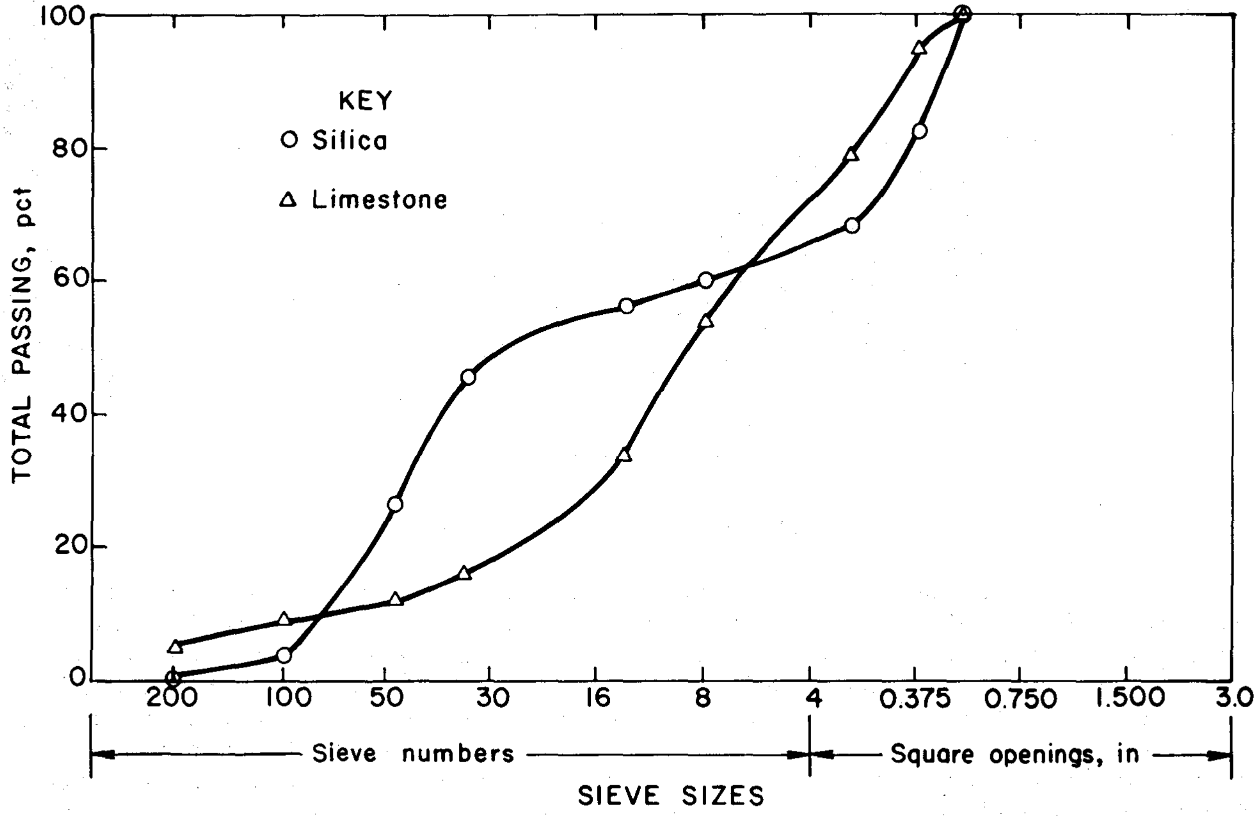

FIGURE 5. - Aggregate gradation chart.

Bulk specific gravity measurements were made in accordance with ASTM Method C 127-73 using the saturated-surface dry basis (1, pp. 77-79). Void contents were determined using ASTM Method C 30-37 (1 p. 7), and the aggregate unit weight was determined by ASTM Method C 29-71 (1, pp. 4-5).

Determination of the optimum binder values using both modified and unmodified sulfur is illustrated by the data given in table 2 for the limestone aggregate.

TABLE 2. - Compressive strengths of limestone mix design specimens

Aggregate, wt-pct	Sulfur,[1] wt-pct	Compressive strength, psi
82	18	5,720
79	21	6,590
78	22	6,740
76	24	6,940
73	27	6,500
83	17M	5,440
80	20M	7,200
79	21M	7,990
77	23M	9,020
74	24M	3,820

[1] M signifies sulfur modified by reaction with 5 wt-pct dicyclopentadiene.

Maximum compressive strengths were attained with unmodified sulfur as the binder at 22 and 24 pct sulfur concentrations and with modified sulfur at 21 and 23 pct sulfur concentration. A similar test using the silica aggregate had optimum strengths with sulfur binders at 24 and 26 pct and with modified sulfur binders at 22 and 24 pct. Less modified sulfur was required to obtain optimum strength with a given aggregate than was required for unmodified sulfur. Diehl (15) has also reported that less sulfur was required when modified sulfur was used. Other advantages in using modified sulfur as the aggregate binder were better wetting of the aggregate and increased stability of the concrete mixtures. Using sulfur as the binder, there is a tendency for the heavier aggregate to segregate to the bottom and the liquid sulfur to rise to the top of the mixture. Rodding or vibrating the material increases the separation. Modified sulfur acts as a thixotropic agent and holds the aggregate in a uniform dispersion. Another advantage of using modified sulfur binders is that better bonding of joints is obtained when making multiple pours of sulfur concrete. This is illustrated in figure 6, which shows fractured sections of two 6- by 6- by 30-inch beams that were poured in four lifts. Each lift was allowed to solidify before the next lift was poured. Flexural testing resulted in delamination of the unmodified sulfur concrete beam. The modified sulfur concrete beam showed crosslinking of the binder and no delamination on breaking.

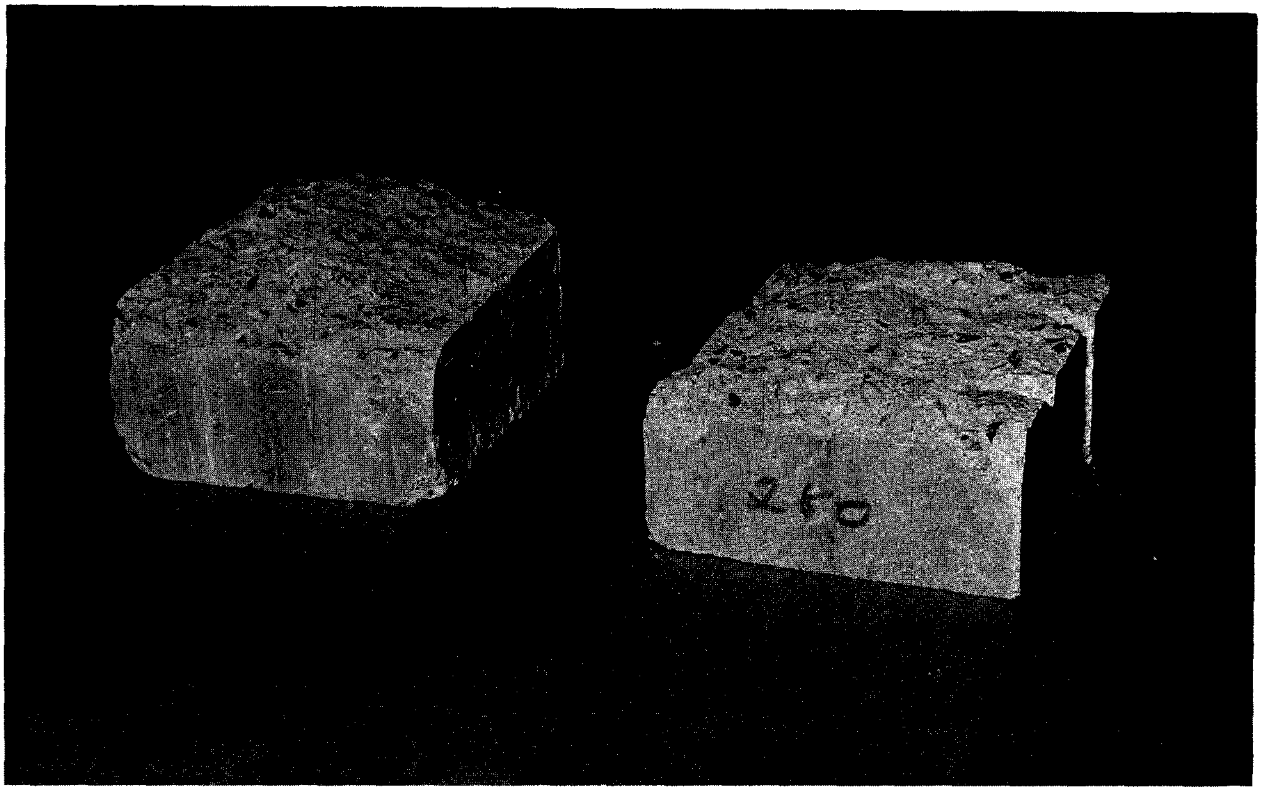

FIGURE 6. - Flexure testing of sulfur concrete beams. Left, modified sulfur concrete; right, unmodified sulfur concrete.

Testing of Sulfur Concretes

Properties

Test specimens of sulfur concrete were prepared from the two aggregates using sulfur binder values corresponding to the two highest compressive strength values determined in the mix design. Resulting test data from the specimens are given in table 3.

TABLE 3. - Properties of sulfur concrete materials

Aggregate	Sulfur,[1] pct	Strength, psi			Sp gr	Voids, pct
		Compressive	Flexural	Tensile		
Silica........	24	5,075	845	730	2.3409	4.0
Do..........	26	7,280	905	830	2.4012	1.0
Do..........	22M	5,310	1,220	775	2.2132	8.6
Do..........	24M	6,120	1,335	760	2.2306	7.2
Limestone.....	22	6,740	700	795	2.4762	1.3
Do..........	24	6,855	810	760	2.4974	0.0
Do..........	21M	7,990	1,235	815	2.4364	2.0
Do..........	23M	9,020	1,330	895	2.4281	1.6

[1] M signifies sulfur that has been reacted with 5 pct dicyclopentadiene.

Sulfur concretes prepared from both aggregates had strength properties in most cases superior to those of high-strength portland cement concretes. Portland cement concrete for building purposes average 2,500 to 3,500 psi compressive strength, and when prestressed will average up to twice these values. For pavements, portland cement concretes are used with compressive strengths of 3,000 to 4,000 psi. In general, these concretes have flexural strengths that are 10 to 15 pct of their compressive strengths, and tensile strengths that are approximately 10 pct of their compressive strengths.

Sulfur concretes prepared with silica aggregates showed little difference in the compressive and tensile strengths of materials prepare with either modified or unmodified sulfur. The flexural strengths of materials prepared using modified sulfur binders were greater than those prepared with unmodified sulfur.

Sulfur concretes prepared with limestone aggregates and modified sulfur had higher strength values than those made with unmodified sulfur. Both compressive and flexural strengths were markedly higher. This may indicate that there is chemical bonding between the limestone aggregate and the sulfur, and since better wetting of the aggregate is obtained with the modified sulfur, a better bond is obtained.

Freeze-Thaw Testing

Prisms of sulfur concrete were subjected to 300 cycles of freezing and thawing. Curves showing relative dynamic moduli of elasticity versus the number of freeze-thaw cycles for the prisms are plotted in figure 7. After samples had completed their freeze-thaw cycling, they were tested to determine their residual flexural strength. Table 4 presents these values along with the original values.

TABLE 4. - Summary of flexural strengths after freeze-thaw testing

Aggregate	Sulfur, pct	Modulus of rupture, psi		Residual strength, pct
		Original	Final	
Silica......	24	845	125	14.8
Do........	26	905	140	15.5
Do........	22M	1,220	285	23.4
Do........	24M	1,335	310	23.2
Limestone...	22	700	235	33.6
Do........	24	810	285	35.1
Do........	21M	1,235	470	38.0
Do........	23M	1,330	400	30.1

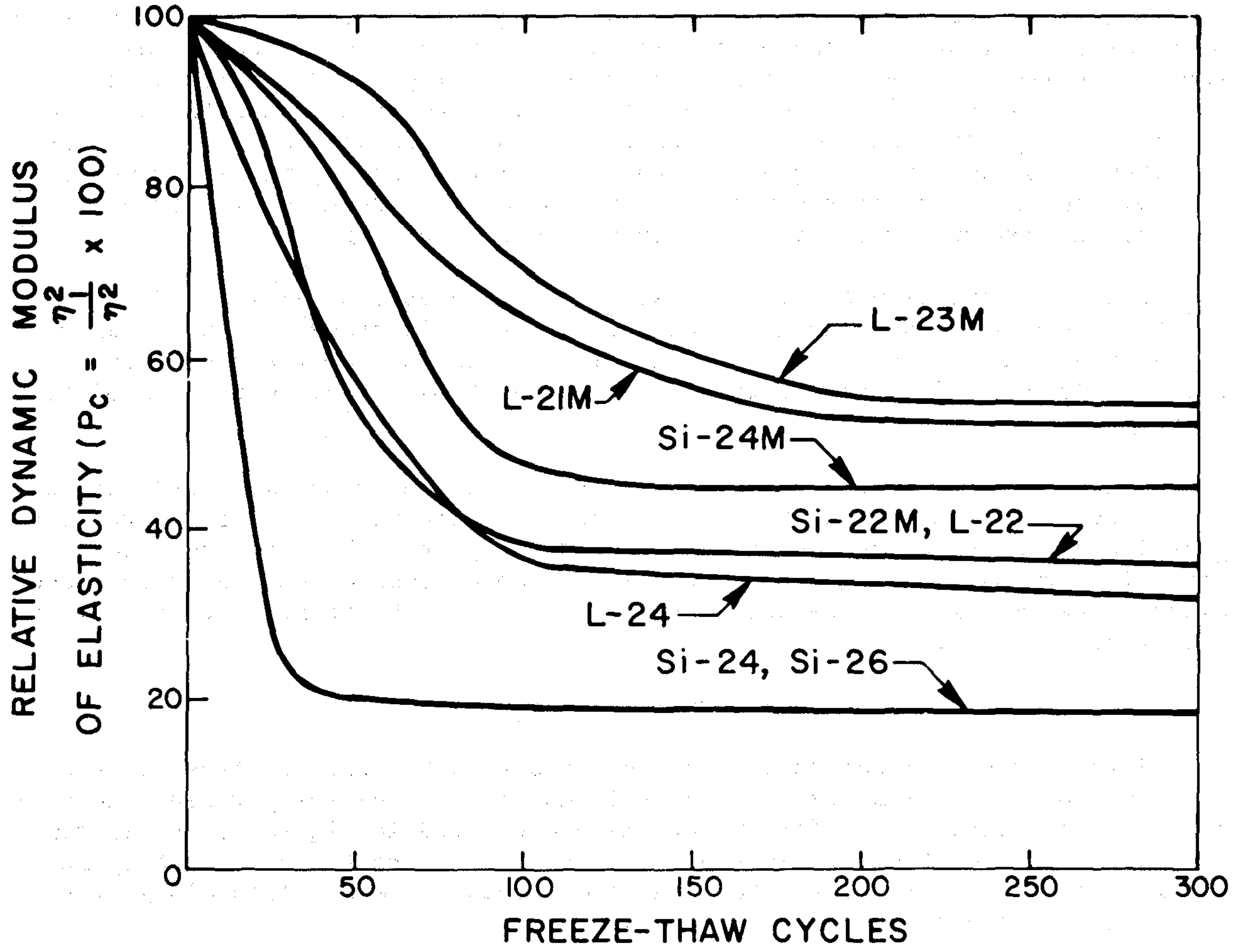

FIGURE 7. - Freeze-thaw testing of sulfur concrete specimens.

All of the test samples were sound after 300 cycles of testing. Residual flexural strengths were greater for the modified sulfur concretes than for the unmodified concretes. Both modified and unmodified sulfur concretes prepared from limestone aggregates retained approximately one-third of their original flexural strengths after 300 freeze-thaw cycles. The silica aggregate sulfur concretes were not as resistant to freeze-thaw damage as were those prepared from limestone. Overall, the residual flexural strengths of the modified sulfur concretes were approximately double those of the unmodified materials. This illustrates the values of using modified sulfur to prepare sulfur concretes. It was also interesting to note in figure 7 that the major damage to the sulfur concrete specimens through freeze-thaw cycling occured within the first 100 cycles. There was very little change between 100 and 300 cycles.

Acid Corrosion Resistance

Data obtained over the 1-year test period showed that the concretes prepared with the silica aggregate and modified sulfur binder were superior to those made with unmodified sulfur binders. Sulfur concretes containing

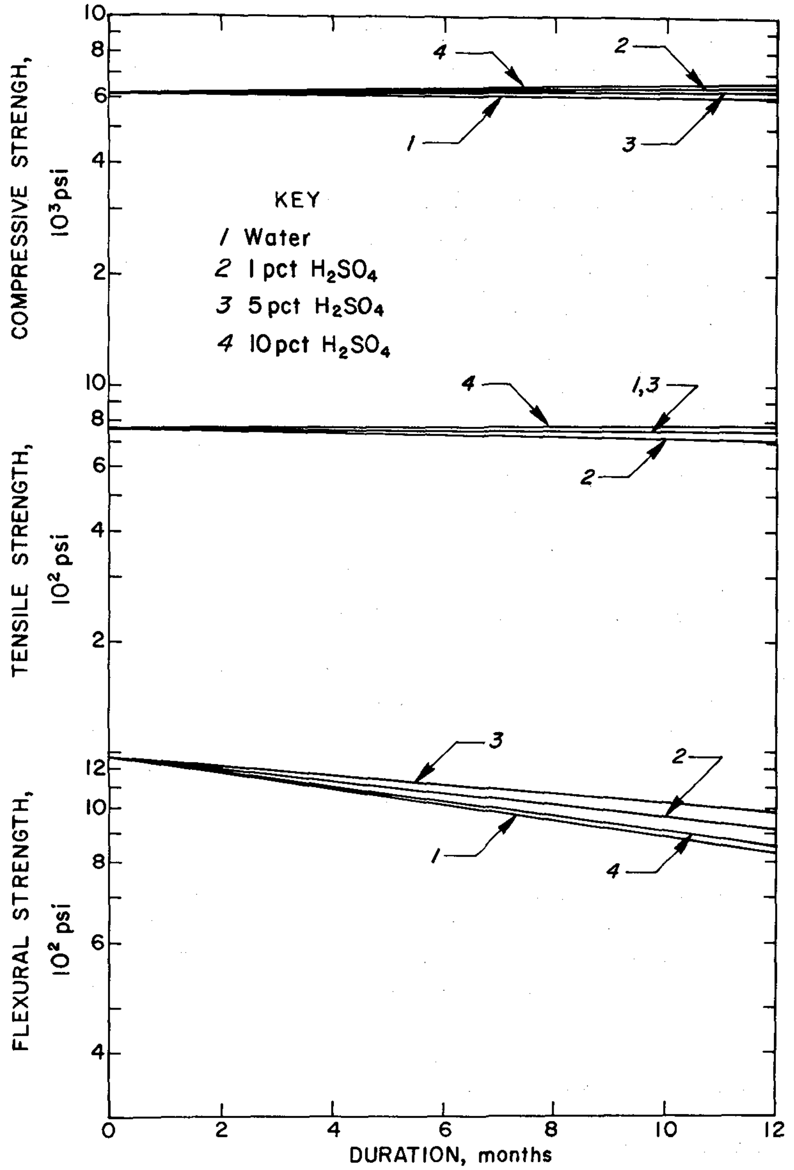

FIGURE 8. - Mechanical properties of sulfur concrete corrosion test specimens.

24 wt-pct modified sulfur had better mechanical properties than those made with 22 wt-pct modified sulfur. The effects on the mechanical properties of test specimens immersed in water and in 1.8, 8.8, and 17.0 wt-pct H_2SO_4 for up to 1 year are illustrated in figure 8 for specimens containing 24 wt-pct modified sulfur. The compressive and tensile strength values were not affected by immersion in the test solutions for a 1-year period. A decrease in flexural strength was found which may be explained as a loss in plasticity of the modified sulfur over the 1-year test period. Even so, the flexural strengths for the modified sulfur concrete samples were higher after 1 year of exposure to the test solutions than the starting values for the unmodified sulfur concretes. Absorption of water or acid solutions into the samples was very slight. Weight gain, in percent, after 1 year of immersion averaged 0.16, 0.15, 0.08, and 0.02 for the sulfur concretes containing 24, 26, 22M, and 24M wt-pct sulfur, respectively. These values were constant over the testing period, which indicated that the amount of moisture penetration into reinforcing material would be very small.

Visual examination of the specimens removed bimonthly showed no evidence of swelling, cracking, or disintegration through the first 10 months. Some of the sulfur concrete samples prepared from 24 and 26 wt-pct unmodified sulfur showed evidence of a slight loss of materials from the surface of the specimen. This was in the form of small pieces that popped from the surface and were indicative of a highly stressed specimen rather than evidence of acid attack on the material. This was confirmed by the fact that the condition was observed both in samples that were immersed in acid solutions and in samples immersed in water alone.

The half-scale electrolytic cell required twenty 350-pound batches of sulfur concrete for its construction. From each batch, 50 pounds was used in preparing test specimens. Data obtained from the test samples are given in table 5.

TABLE 5. - Sulfur concrete test cell data

Location	Strength, psi			Voids, pct
	Compressive	Flexural	Tensile	
Floor.................	5,200	1,480	685	6.9
North wall............	5,900	1,360	780	5.8
South wall............	5,200	1,220	730	6.0
East wall.............	5,550	1,170	700	6.7
West wall.............	5,300	1,150	715	6.9
NW corner.............	4,900	1,160	775	4.4
SW corner.............	4,970	1,260	710	5.5
SE corner.............	4,990	1,100	660	3.6
NE corner.............	4,800	1,080	750	6.5
Average..........	5,200	1,220	725	5.8

Strength properties of the sulfur concrete in the cell are consistent with the values obtained previously on smaller batches of the mix. The cell has been in operation for 18 months with the circulating solution and no evidence of any corrosion or erosion of the concrete has appeared. In addition, there are no signs of any moisture penetrating from the inside of the cell walls.

Results from corrosion testing by the two test methods have shown that an acid-resistant sulfur concrete can be fabricated from silica aggregate and modified sulfur binders. Exposure of the concretes to acid solutions for 1 year has caused negligible corrosion or erosion, and strength properties have been retained.

Salt Corrosion Resistance

Results from the test showed no measurable attack on the specimens on exposure to the salt solutions for 1 year. None of the specimens showed a loss in weight, and the gains in weight from absorption were in the zero to 0.30 pct range. As in the acid-corrosion test, the greater absorption was with specimens of both aggregates that were prepared with unmodified sulfur. Strength properties showed no signs of deterioration on exposure to the salt solutions. The best mixtures contained 77 wt-pct limestone aggregate with 23 wt-pct modified sulfur and 76 wt-pct silica aggregate with 24 wt-pct modified sulfur. There was no evidence that any of the three salt solutions had any deleterious effect on the sulfur concretes. For example, typical strength values of the sulfur concrete containing 77 wt-pct limestone and 23 wt-pct modified sulfur after 1 year of immersion in a 5 vol-pct salt solution follow in pounds per square inch: Compressive strength, 8,600; flexural strength, 1,100; and splitting tensile strength, 835.

Sulfur concretes prepared from silica or limestone aggregates and modified sulfur binders were not affected by exposure to NaCl, $CaCl_2$, or Na_2SO_4 salt solutions. High-strength sulfur concretes were prepared using limestone aggregates with a compressive strength of approximately 9,000 psi that could be used in applications where salts cause failure of portland cement concretes. Some examples include sulfur concrete bridge decking for highway construction and use as floors in plants, such as those making sodium sulfate, where salt solutions cause failure of portland cement concrete. The lower compressive strength (6,000 psi) silica concretes are adaptable for use in either salt or acid environments.

SUMMARY

Corrosion-resistant, highly durable sulfur concrete using limestone and quartz aggregates with modified sulfur as the cementing agent were developed for specialized applications. Test results indicate that the modifier (5 pct dicyclopentadiene) enhances the freeze-thaw durability and lowers absorption of liquids.

Optimum mixture designs were 77 pct limestone aggregate or 76 pct quartz aggregate with the remainder modified sulfur. Sulfur quartz aggregate concrete had moderately high-strength characteristics (6,000 psi compressive) and was extremely resistant to chemical attack by both acid and salt solutions. The sulfur limestone aggregate concrete exhibited high-strength characteristics (9,000 psi compressive) and was extremely resistant to chemical attack by salt solutions.

Both concretes maintained their strength and integrity after 1 year of exposure in solutions consisting of water, 1.8, 8.8, or 17.0 pct H_2SO_4, 5 pct $CaCl_2$, 5 pct Na_2SO_4, and 5 pct NaCl. These concretes displayed good resistance to damage by freeze-thaw cycling. Test bars subjected to 300 cycles were sound and showed no evidence of cracking or disintegration.

A 400-gal, half-scale electrowinning cell, constructed with modified sulfur quartz aggregate concrete, exhibited no signs of corrosion or erosion after 18 months of testing with circulating 8.8 pct H_2SO_4.

Sulfur concrete should find future application in many specialty areas where portland cement concrete are not completely satisfactory, such as leach tanks, electrolytic cells, thickeners, bridge decking, industrial flooring, pipe, and tile.

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