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EFFECT OF SPECIMEN SIZE ON COMPRESSIVE STRENGTH OF SULPHUR CONCRETE

by

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SUMMARY OF RESULTS

The compressive strengths of 4 x 8-in. (102 x 203-mm) sulphur concrete cylinders are considerably higher than those of 6 x 12-in. (152 x 305-mm) cylinders. For a typical sulphur concrete mix containing about 25 per cent sulphur, the 28-day compressive strengths of 4 x 8-in. cylinders range from 4785 to 6730 psi (32.8 to 46.2 MN/m^2), whereas the corresponding strengths of 6 x 12-in. cylinders range from 3790 to 5005 psi (26.1 to 34.4 MN/m^2).

The densities of 4 x 8-in. cylinders are generally higher than those of 6 x 12-in. cylinders. For 28-day test results, the densities of 4 x 8-in. cylinders range from 149.05 to 151.57 lb/ft^3 (2388 to 2428 kg/m^3); the corresponding values for 6 x 12-in. cylinders range from 149.05 to 150.48 lb/ft^3 (2388 to 2411 kg/m^3). The decrease in strength of large specimens is probably due to the combined effects of specimen size and slower rate of cooling.

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INTRODUCTION

During the past five years, a large surplus of sulphur has developed in Canada. This is primarily due to the introduction of a large number of sour gas processing plants in Alberta during the late sixties. In these plants, hydrogen sulphide is removed and converted to sulphur before the natural gas is distributed to the users. Another source of sulphur contributing to the surplus has been the recovery of sulphur during the refining of oil as a result of strict pollution control regulations. Because huge inventories and stockpiles have been fast building up since 1970, the Mines Branch initiated a limited research program in 1972 to find new uses for sulphur. In 1973, an investigation report was issued which dealt with the development of satisfactory procedures for mixing sulphur concrete, its mechanical properties and its resistance to freezing and thawing(1). In that investigation, all compression tests were made on 4 x 8-in. (102 x 203-mm) cylinders; however, in the concrete industry the standard compression test specimen is a 6 x 12-in. (152 x 305-mm) cylinder. The present investigation was therefore undertaken to determine the effect of specimen size on the compressive strength of sulphur concrete.

MATERIALS USED

Commercial sulphur, 99.9 per cent pure, was used in this investigation. The percentages retained on 200- and 325-mesh screens were 24.3 and 26.9 per cent respectively, with 48.8 per cent passing minus 325 mesh. Coarse aggregate was river gravel crushed to minus 3/4 in. (19 mm), and fine aggregate was a local sand. To keep the size distribution uniform, the sand was separated and recombined in specified size fractions. The grading and physical properties of the coarse and fine aggregates are shown in Tables 1 and 2. Silica flour was used as a workability aid in all the mixes.

MIX PROPORTIONS

The mix proportions selected for this investigation, expressed in per cent of total weight of aggregates, were as follows:

Fine aggregate	-	40 per cent
Coarse aggregate	-	60 " "
Sulphur	-	25 " "
Silica flour	-	6 " "

The batch weights, using the above proportions, were as follows:

Fine aggregate	-	32.0 lb (14.5 kg)
Coarse aggregate	-	48.0 " (21.8 kg)
Sulphur	-	20.0 " (9.1 kg)
Silica flour	-	4.8 " (2.18 kg)

MIXING PROCEDURE

A 2.5 cu-ft, tilting-drum, electrically operated mixer was used. Its diameter was 18 in. (45.7 cm) at the top, 24 in. (61 cm) at the bottom, and its length was 24 in. (61 cm). The outside of the drum was wrapped with asbestos sheeting to minimize heat loss during mixing. The weighed aggregates were placed in tin pails and heated overnight in conventional laboratory heating cabinets at 400°F (204.4°C). The following morning, the coarse aggregates were placed in the tilting mixer, which was then started. Immediately afterwards, about 10 lb (4.5 kg) of sulphur were added to coat the aggregates finely; then the sand, the remaining sulphur and the silica flour were added consecutively. Mixing was continued for one more minute, by which time the sulphur and aggregates had combined to form a flowable mixture.

PREPARATION AND TESTING OF SPECIMENS

A series of 18 concrete batches was made, and from each batch usually two 6 x 12-in. (152 x 305-mm) and two 4 x 8-in. (102 x 203-mm) cylinders were cast. In some instances, one 6 x 12-in. (152 x 305-mm) cylinder was withdrawn from the test program and used for demonstration purposes. Cylinder moulds and test cylinders are shown in Figures 1 and 2.

The moulds for all cylinders were filled in one continuous layer and compacted simultaneously by hand rodding, using a 24 x 0.75-in. (605 x 19-mm) steel rod with a hemispherical end. Extra concrete was placed on top of the cylinders to allow for shrinkage of the sulphur. After casting, all the moulded specimens were allowed to cool in the laboratory air for two hours and were then removed from the moulds. At the end of selected curing periods at room temperature, the top quarter-inch (6.3 mm) of each test cylinder was sawn off to remove the excess material and obtain a flat surface. The cylinders, at various ages, were tested in compression on an Amsler testing machine having a capacity of 600,000 lb (271,800 kg), in accordance with ASTM Standard Methods*.

TEST RESULTS AND THEIR ANALYSIS

Eighteen batches of sulphur concrete were made, and a total of thirty-eight 6 x 12-in. (152 x 305-mm) cylinders and thirty-five 4 x 8-in. (102 x 203-mm) cylinders were tested in this program. The density and compressive strength test results are summarized in Tables 3 to 7. Where possible,

* ASTM Standard Method C 39-72.

standard deviations and coefficients of variation for the test data were calculated; these are shown in Tables 8 and 9.

The plots of the compressive strengths and densities for the data under analysis are shown in Figures 3 and 4, on which lines of equality are also shown.

DISCUSSION OF TEST RESULTS

Size Effect

Tables 3 to 7 and Figure 3 show that compressive strengths of 6 x 12-in. (152 x 305-mm) cylinders are considerably lower than those of 4 x 8-in. (102 x 203-mm) cylinders. This is true at all ages. At one day, the ratio of the strength of 4 x 8-in. (102 x 203-mm) cylinders to that of 6 x 12-in. (152 x 305-mm) cylinders, expressed as a percentage, is between 122.0 and 176.5 per cent. The corresponding ratio at 28 days is between 104.2 and 146.1 per cent.

By comparison, for Portland cement concrete the ratio of the strength of 4 x 8-in. (102 x 203-mm) cylinders to that of 6 x 12-in. (152 x 305-mm) cylinders is between 84 and 152 per cent [(2)]. For the same type of Portland cement concrete, the U.S.B.R. [(3)] has reported an average value of 104 per cent.

Density Effect

It has been suggested that what is being considered as a "size" effect may actually be a density effect because the densities of 4 x 8-in. (102 x 203-mm) cylinders are greater than the densities of 6 x 12-in. (152 x 305-mm) cylinders. The limited data reported in this investigation partially support this hypothesis. Except for two batches of sulphur concrete that were tested at 70 days, and one batch that was tested at 28 days (Figure 3), the densities of 4 x 8-in. (102 x 203-mm) cylinders are considerably higher than those of 6 x 12-in. (203 x 305-mm) cylinders. The difference in densities between the two sizes of cylinders probably results from different compacting effort in the two cases. The slow rate of cooling probably affects the size and shape of the sulphur crystals but not the density of test specimens. One-inch thick sections cut from large and small cylinders of sulphur concrete are shown in Figure 5.

Summation - Strength Theory

Tucker[(4)] has tried to explain the specimen size effect on strength test results by means of the Summation - Strength Theory. According to this theory:

(a) the strength of material is independent of the area of the specimen upon which tests are made, provided that the length of the specimens remains unchanged in tension tests and that the length-diameter ratio is constant in compression tests.

(b) the standard deviation of the compressive strength decreases with increase in cylinder diameter; however, equal information is obtained when the numbers of cylinders tested are such that the summation of the cross sectional areas of the cylinders of the two sizes are equal.

The test results presented here do not appear to fully support the first part of the theory: for the same length-diameter ratio (this equals 2 for the cylinder sizes investigated in this report), there is a decrease in strength with increase in the diameter of the specimen. However, this loss of strength may be due partially to the slower rate of cooling of sulphur concrete in large cylinder moulds with consequent formation of larger crystals and a weaker structure. As to the second premise of the theory, the number of test results under analysis is insufficient to draw any positive conclusions.

CONCLUDING REMARKS

The compressive strengths of 6 x 12-in. (152 x 305-mm) cylinders are considerably lower than those of 4 x 8-in. (102 x 203-mm) cylinders. This decrease in the strength of large specimens is probably due to the combined effect of specimen size and slower rate of cooling of sulphur concrete in large specimens while still in the moulds. This aspect of sulphur concrete could pose serious problems in its use for structural concrete members - problems which would have to be overcome by either controlling cooling rates or designing members in such a way that their thickness is kept to a minimum and a large surface area is provided.

There are insufficient data to determine the effect of increase in test specimen diameter on the standard deviation of the compressive strength test results.

REFERENCES

1. V. M. Malhotra, "Mechanical Properties and Freeze-thaw Resistance of Sulphur Concrete", Mines Branch Investigation Report IR 73-18, January 1973, 30 pp.

2. V. M. Malhotra, "Are 4 x 8-in. Concrete Cylinders as Good as 6 x 12-in. Cylinders for Quality Control of Concrete?", Mines Branch Investigation Report IR 73-35, May 1973, 47 pp.

3. "Concrete Manual", 7th Edition, United States Bureau of Reclamation, 1963, p 582.

4. John Tucker, "Effect of Dimensions of a Specimen Upon the Precision of Strength Data", Proceedings, ASTM, V 45, 1945, pp 952-959, Discussion, p 960.

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TABLE 1

Grading of Aggregates

Coarse Aggregate				Fine Aggregate		
Sieve size		Cumulative percentage retained		Sieve size		Cumulative percentage retained
		Grading A*	Grading B**			
3/4 in.	19.0 mm		–			
1/2 in.	12.5 mm	0	50.0			
3/8 in.	9.5 mm	50.0	85.0			
No. 4	4.75mm	100.0	100.0	No. 4	4.75 mm	0
				No. 8	2.36 mm	10.0
				No. 16	1.18 mm	32.5
				No. 30	600 µm	57.5
				No. 50	300 µm	80.0
				No. 100	150 µm	94.0
				Pan		100.0

* Used for Mix No. 1.
** Used for Mix No. 2 to 11 inclusive.

TABLE 2

Physical Properties of Coarse and Fine Aggregates

	Crushed gravel	Natural sand
Specific gravity	2.72	2.70
Absorption, %	0.40	0.50

TABLE 3

Summary of One-Day Compressive Strength Test Results

Mix No.	6x12-in.(152x305-mm) Cylinders				4x8-in.(102x203-mm) Cylinders			
	Density		Compressive Strength,		Density,		Compressive Strength,	
	lb/ft^3	kg/m^3	psi	MN/m^2	lb/ft^3	kg/m^3	psi	MN/m^2
1	147.31	2360	3480*	23.9	149.53	2395	5610	38.5
2	149.77	2399	3680*	25.3	150.50	2411	5820	40.0
3	151.09	2420	4140*	28.4	151.99	2435	6435	44.2
4	150.49	2411	4600*	31.6	150.78	2415	5610	38.5
5	149.48	2395	3785*	26.0	150.36	2409	5515	37.9
6	150.85	2417	3890*	26.7	151.20	2422	5255	36.1
7	145.81	2336	2865	19.7	146.55	2347	5060	34.7

<u>Note:</u> Each value is the average of two test results unless otherwise indicated.
* Only one cylinder tested.

TABLE 4

Summary of 7-day Compressive Strength Test Results

Mix No.	6x12-in.(152x305-mm) Cylinders				4x8-in.(102x203-mm) Cylinders			
	Density		Compressive Strength,		Density,		Compressive Strength,	
	lb/ft^3	kg/m^3	psi	MN/m^2	lb/ft^3	kg/m^3	psi	MN/m^2
8	149.02	2387	3660	25.1	149.17	2390	4580	31.5

<u>Note</u>: Each value is the average of two test results.

TABLE 5

Summary of 28-Day Compressive Strength Test Results

Mix No.	6x12-in.(152x305-mm) Cylinders				4x8-in.(102x203-mm) Cylinders			
	Density		Compressive Strength,		Density,		Compressive Strength,	
	lb/ft^3	kg/m^3	psi	MN/m^2	lb/ft^3	kg/m^3	psi	MN/m^2
9	150.48	2411	4600	31.6	151.57	2428	6730	46.2
10	148.29	2376	4280	29.4	149.05	2388	5615	38.6
11	149.05	2388	4810	33.0	149.77	2399	5295	36.4
12	-	-	5005	34.4	-	-	5215	35.8
13	150.36	2409	3790	26.0	150.29	2408	4785	32.9

<u>Note</u>: Each value is the average of two test results.

TABLE 6

Summary of 70-Day Compressive Strength Test Results

Mix No.	6x12-in. (152x305-mm) Cylinders				4x8-in. (102x203-mm) Cylinders			
	Density,		Compressive Strength,		Density,		Compressive Strength,	
	lb/ft^3	kg/m^3	psi	MN/m^2	lb/ft^3	kg/m^3	psi	MN/m^2
14	148.88*	2385	4810*	33.0	151.20	2422	4895	33.6
15	149.05	2388	4585	31.5	150.35	2409	6230	42.8
16	150.39	2409	4210	28.9	147.94	2370	5455	34.5
17	150.58*	2412	3645*	25.0	150.02*	2403	6845*	47.0

Note: Each value is the average of two test results.

* Only one cylinder tested.

TABLE 7

Summary of 90-Day Compressive Strength Test Results

Mix No.	6x12-in. (152x305-mm) Cylinders				4x8-in. (102x203-mm) Cylinders			
	Density,		Compressive Strength,		Density,		Compressive Strength,	
	lb/ft^3	kg/m^3	psi	MN/m^2	lb/ft^3	kg/m^3	psi	MN/m^2
18	--	-	3735	25.6	149.28	2391	5115	35.1

Note: Each value is the average of two test results.

TABLE 8

Within-Batch Standard Deviation and Coefficient of Variation For One-Day Test Results

Mix No.	6x12-in. (152x305-mm) Cylinders					4x8-in. (102x203-mm) Cylinders				
	Compressive Strength		Standard Deviation		Coefficient of Variation, per cent	Compressive Strength		Standard Deviation		Coefficient of Variation, per cent
	psi	MN/m^2	psi	MN/m^2		psi	MN/m^2	psi	MN/m^2	
1	3480*	23.9	-	-	-	5610	38.5	170	1.2	3.0
2	3680*	25.3	-	-	-	5820	40.0	124	0.8	2.1
3	4140*	28.4	-	-	-	6435	44.2	354	2.4	5.5
4	4600*	31.6	-	-	-	5610	38.5	619	4.2	11.0
5	3785*	26.0	-	-	-	5515	37.9	85	0.6	1.5
6	3890*	26.7	-	-	-	5255	36.1	453	3.1	8.6
7	2865	19.7	0	0	0	5060	34.7	506	3.5	10.0

*Only one cylinder tested.

TABLE 9

Within-Batch Standard Deviation and Coefficient of Variation for 28-Day Test Results

Mix No.	6x12-in. (152x305-mm) Cylinders					4x8-in. (102x203-mm) Cylinders				
	Compressive Strength		Standard Deviation		Coefficient of Variation, per cent	Compressive Strength		Standard Deviation		Coefficient of Variation, per cent
	psi	MN/m^2	psi	MN/m^2		psi	MN/m^2	psi	MN/m^2	
9	4600	31.6	148	1.0	3.2	6730	46.2	279	1.9	4.2
10	4280	29.4	251	1.7	5.9	5615	38.6	166	1.1	3.0
11	4810	33.0	400	2.7	8.3	5295	36.4	1068	7.3	20.2
12	5005	34.4	824	5.7	16.5	5215	35.8	841	5.8	16.1
13	3790	26.0	450	3.1	11.9	4785	32.9	518	3.6	10.8

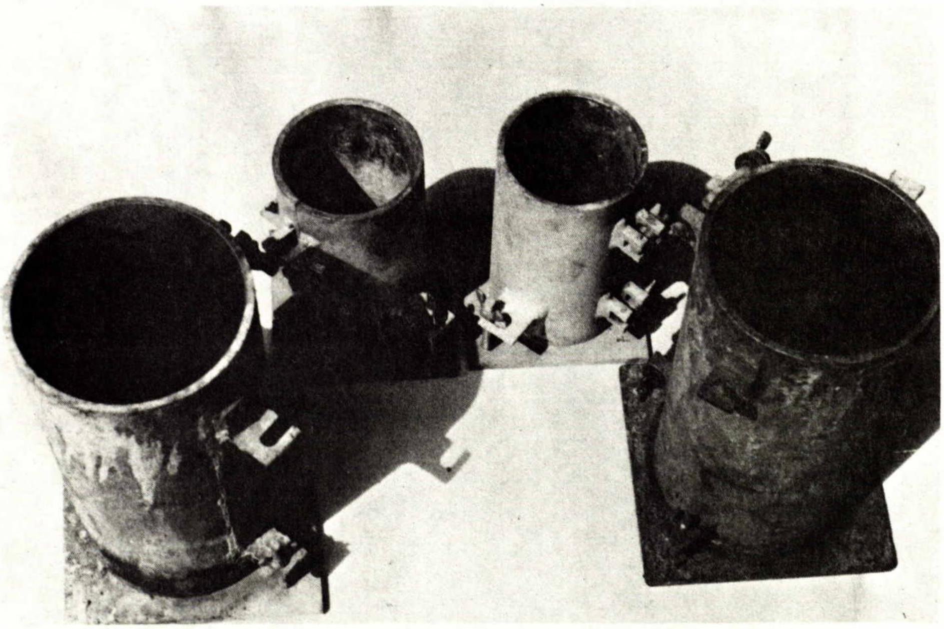

Figure 1: A view of 4 x 8-in. (102 x 203-mm) and 6 x 12-in. (152 x 305-mm) heavy-duty steel moulds.

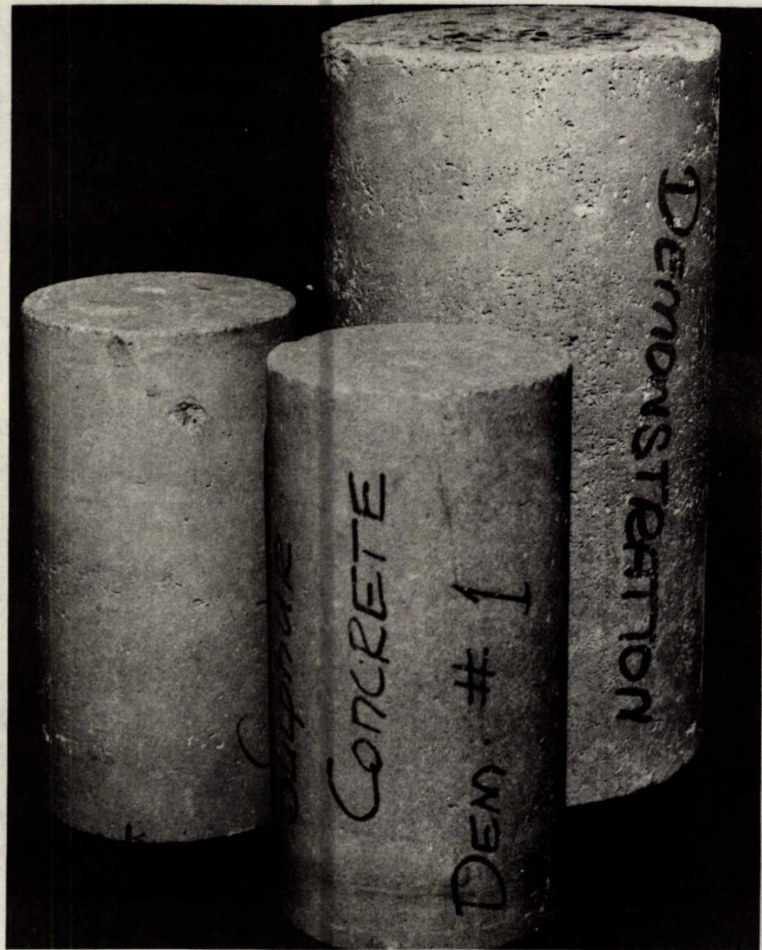

Figure 2: A view of 4 x 8-in. (102 x 203-mm) and 6 x 12-in. (152 x 305-mm) cylinders.

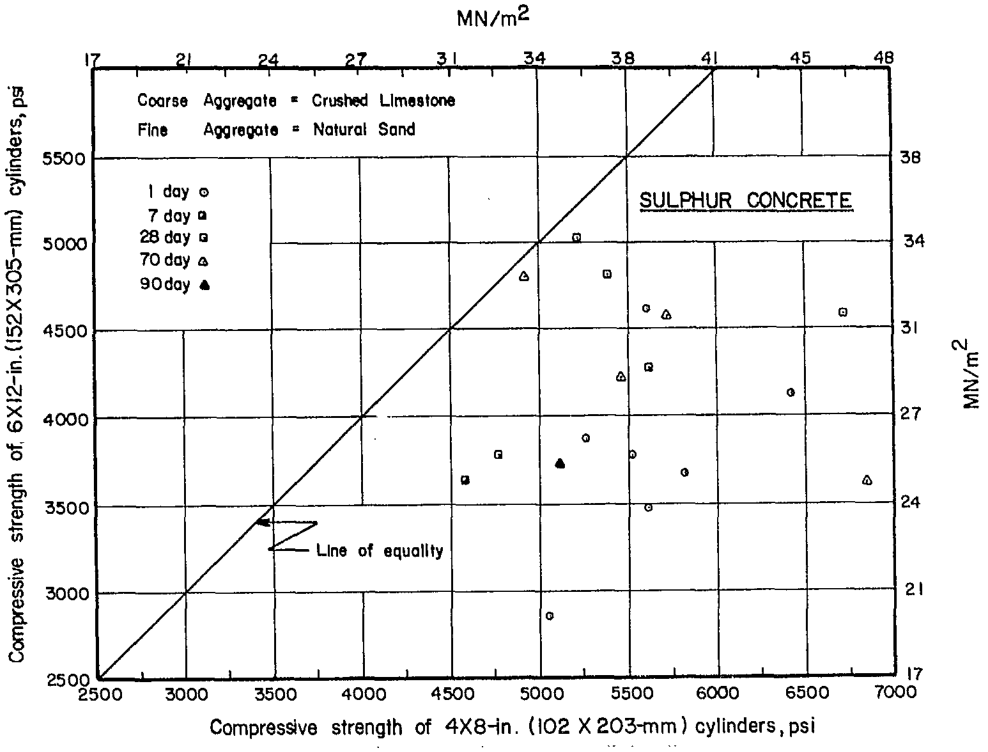

Figure 3: Relationship between compressive strengths of 4 x 8-in. (102 x 203-mm) and 6 x 12.-in. (152 x 305-mm) cylinders

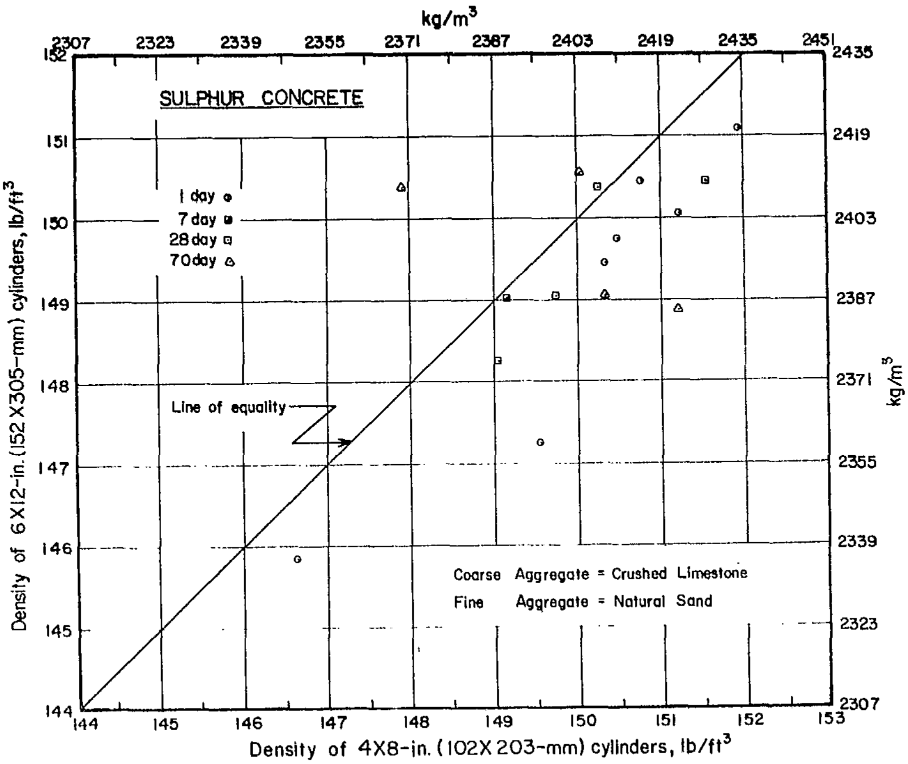

Figure 4: Relationship between densities of 4 x 8-in. (102 x 203-mm) and 6 x 12-in. (152 x 305-mm) cylinders

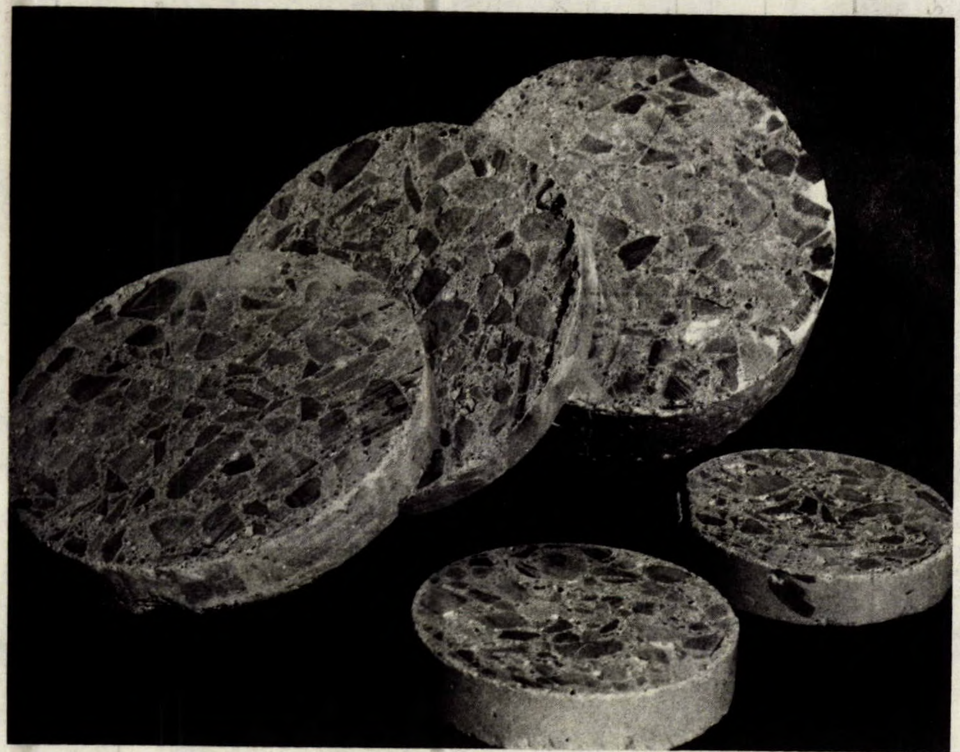

Figure 5: A view of one inch- (25.4 mm)-thick slices cut from cylinders of sulphur concrete.