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Investigations of the feasibility of transporting ore in open-flumes.

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INVESTIGATIONS OF THE FEASIBILITY OF

TRANSPORTING ORE IN OPEN-FLUMES

BY

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A

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ABSTRACT

Considerable effort has been expended and many data are published on developing the technologies of pipeline transportation and hydraulic hoisting. However, comparatively little information is available on the techniques of hydraulic mining, and nearly none is reported on conveying slurries in open flumes. For this reason, the author chose to investigate some of the parameters that influence open-flume transport.

It was found that Durand has assembled the findings of several investigators into a simple mathematical expression which is accepted as a standard for designing slurry pipelines. Further investigation by the writer revealed that Durand's formula, with only minor modification, could be applied to the design of open flumes with equal dependability. This eliminated any pressing need for further study into the "established" flow conditions in flumes.

The above findings caused all research efforts to be directed toward developing basic data which may be used for designing a hydraulic gathering system for conveying mine products into a flume as they are dislodged from the mine face by means of a water monitor. This system involved the flushing of broken solids along the mine bottom and into an open flume. The influence of particle size, specific gravity, bottom slope and water flow rate were determined and analysed. Although the resulting data are of insufficient scope to permit the direct design of a commercial flume system, it is

believed that a suitable pilot installation could justifiable be attempted. A hypothetical design calculation is presented to demonstrate the usability of these findings.

ACKNOWLEDGEMENT

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INTRODUCTION

Hydraulic methods of mining and transportation are rapidly gaining popularity throughout the entire world. Their inter-compatibility and joint simplicity offer a new concept to certain types of mining operations. Where applicable, this combination of mineral winning and handling systems apparently offers an economical means of high productivity.

Long and short distance transportation of solids-water slurries in pipelines has already been accepted as being highly competitive with current conventional methods. The successes that have been experienced with several overland pipelines have prompted the renewal of studies and full scale trials of the related systems of hydraulic mining, open-flume conveying, and hoisting.

The published reports concerning these systems normally stress their individual advantages, which in themselves appear to be logical and significant. However, an overall review of this literature leaves the impression that an integrated all-hydraulic mining operation will benefit from independent advantages of the unit systems and, to an even greater extent, from the combined effects of their mutual adaptability.

Unfortunately, such an integrated operation has not as yet received the promising acceptance of the slurry pipeline. Its

greatest apparent handicap being the lack of technological development in the system of mining and hoisting, and especially in open-flume conveying. Research efforts are being directed toward this goal and the results, to date, are very gratifying.

An integrated hydraulic operation would apparently be ideal for mining the pitching, low grade coal deposits of India where a high degree of conventional mechanization is not practicable. The ever increasing industrial demands upon these areas are constantly exceeding maximum production rates whereas the seam conditions are gradually becoming less conducive to greater mechanical productivity.

Hydraulic Mining

Materials such as Borax, Sulphur, Potash, Phosphate, Salt, Gravel, Clay, and Coal are currently being mined by means of high pressure water jets. The jetting nozzles (monitors) (Figure 1) are maneuvered manually or mechanically so as to produce a cutting-wedging action, at pressures ranging to 4000 psi, to dislodge the materials from a solid working face and flush them into a dewatering screen or sump from whence they are transported out of the mine by an appropriate separate system. The dewatered products may be conveyed on belts or pans or be carried in mine cars. However, a hydraulic system, such as a pipeline or more logically a flume, would appear most effective for transporting the run-of-mine slurries when conditions are suitable.

The hydraulic monitor has been used with various degrees of success in a large number of surface mining operations during the past century. Recent, improved nozzle designs and the evolution of high pressure pumps have drastically expanded the applicability of this system so that, at the present time, hydraulic mining is being applied underground with excellent efficiencies. It has been shown to be particularly well suited to uniformly pitching coal seams ranging to 30 feet in thickness. (Figure 2)

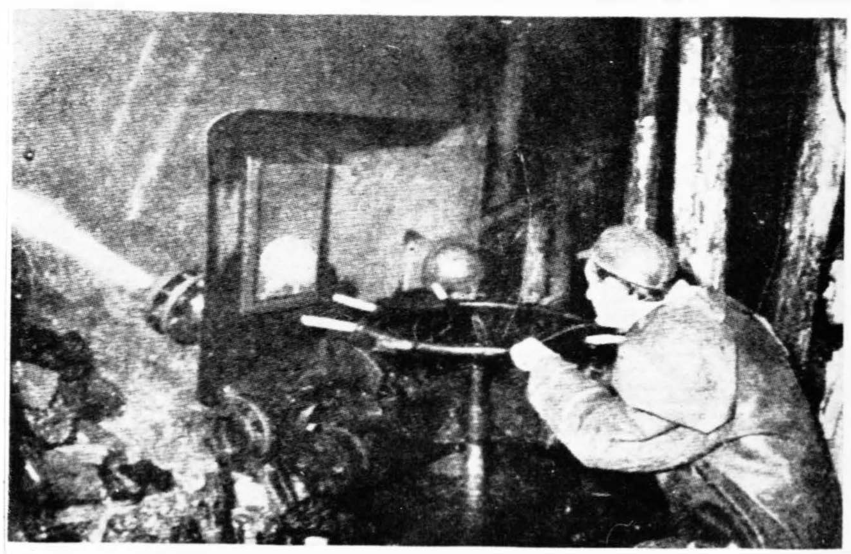

Figure 1. Underground Hydraulic Monitor in the U.S.S.R. (35)

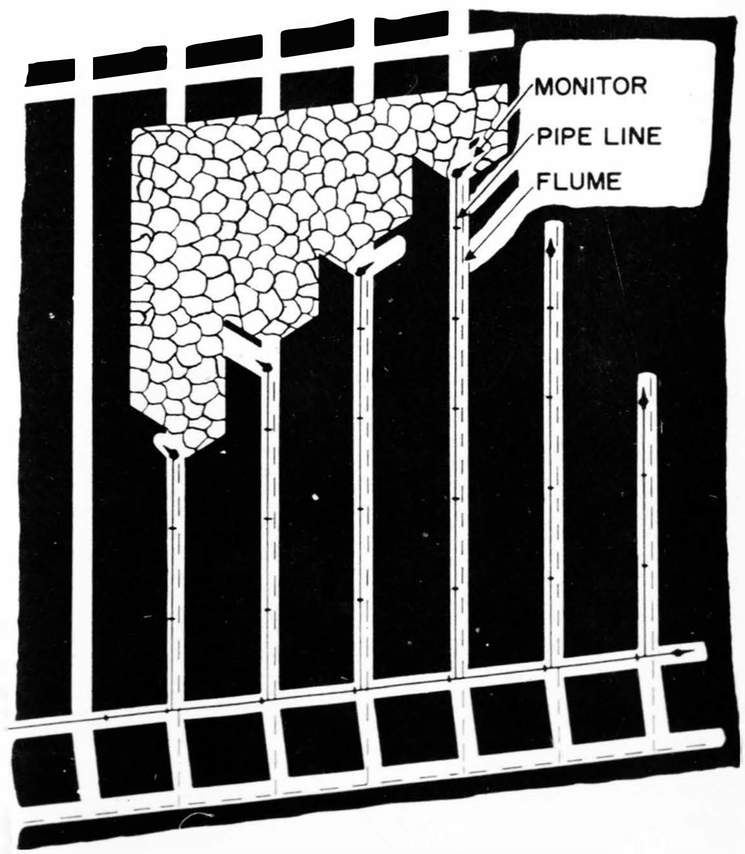

Figure 2. Underground Hydraulic Coal Mining in U.S.S.R. in Gently Pitching Seams. (35)

Where conditions are conducive, hydraulic mining has been demonstrated to offer the following advantages over conventional systems:

1. A significant reduction in mining costs.
2. An increase in face productivity.
3. Decreased initial and maintenance costs of face machinery.
4. Blasting and explosives hazards are eliminated.
5. A clearer and safer face atmosphere results directly from mining.
6. Power cable hazards are reduced.
7. Broken material can be conveyed hydraulically without rehandling or treatment.

On the other hand, a strong roof and stable bottom, and a plentiful source of water are obviously essential.

Hydraulic Transportation

A few integrated hydraulic transportation systems (fluming, hoisting and pipelining) are presently being used to move fine, low-density materials at a limited number of mining operations throughout the world. Most of these have been developed by trial-and-error or by empirical rules derved from those installations which were gradually modified to a successfull status through persistent observation and improvement. In only rare, recent instances have completely integrated systems been designed with any substantial involvement of basic theoretical principles. Many agencies are constantly striving to improve the technology of hydraulic transportation but considerable research data are still needed.

Apparently, a great many ore bodies are sutiably situated for complete hydraulic exploitation but their development for this mode of operation is prevented by the lack of sound, engineering know-how. Any research that may be devoted toward expanding this knowledge will obviously be justified.

Open Flumes

A study of the basic parameters involved in open-flume transportation of solids-water slurries has not been thoroughly investigated. Some investigations have been conducted, in Russia

and at the Missouri School of Mines and Metallurgy, in flow characteristics of coal slurries. Some relationships to pipeline flow have been observed and still others are suspected. These studies are still in the initial stages and the current findings are therefore of only minor significance.

Although the advantages of flume haulage have not been clearly and completely defined, the importance of such a system to a hydraulic mining operation is quite obvious.

Hoisting

An appreciable amount of research has been conducted with hydraulic hoisting during the past decade. Many countries have reported gratifying results in moving solids of various particle sizes, solids-concentration, and specific gravities. Modern systems are hoisting mineral slurries at rates exceeding 1000 tph, in plus 60 percent (by weight) solids concentrations, and with run-of-mine particle sizes ranging to 18 inches in diameter. Vertical hydraulic lifts beyond 1000 feet are becoming commonplace.

This type of system is particularly suited to hoisting fine, light materials but, as exemplified above, it can be modified to handle all types of solids with commensurate reductions in operating efficiencies.

The slurry flow characteristics in vertical hoisting differ from those in horizontal pipelines in that the rising particles act as solid bodies falling in an obstructing medium whereas horizontally flowing solids are affected by a non-linear combination of forces caused by gravity and momentum of the carrying fluid. This results in a greatly reduced flow resistance in the vertical system.

The obstruction of vertically falling solids is actually increased by the presence of additional particles. For example, it has been demonstrated that an 8 percent solids concentration decreases the falling rate by roughly 50 percent as compared to that of a single particle. Furthermore, the size and concentration of the solids have no apparent influence upon the flow resistance within the practical operating limits.

In any case, the insertion of normal mine products into a flowing water column will increase static pumping head which, in turn, will increase hoisting costs. However, under proper circumstances, these may still be far below those of conventional mechanical systems.

Other advantages observed through practice are as follows:

1. Slurry pipes occupy very little shaft space.
2. Initial investment cost is relatively low.
3. Operating costs are low because of good power efficiency.
4. Excellent adaptability to other hydraulic materials handling systems.

Pipelines

Pipeline transportation of solids-water slurries has probably received more attention than all of the other systems combined. Large volumes of data have been compiled and combined to create some degree of confusion but, more importantly, to provide a substantial scientific basis for the development of design principles. As a result, pipelines have been accepted as a standard mode of materials handling. Long-distance systems are presently offering keen competition to other forms of transportation in handling various fluid and solid commodities and additional overland lines are still being planned. It is believed that the true potential of this method has not been fully realized at the present time and that its future will be more significant than is now indicated.

Pipeline transportation offers obvious advantages to under-developed areas such as exist in parts of India where industrialization efforts are constantly hampered by transportation

shortages. Suitable raw materials are available in many isolated areas but their supply to points of consumption are proving difficult if not impossible for lack of bulk haulage facilities.

The construction of roads and railway systems is costly and time consuming whereas pipelines may be installed rapidly, with relatively less investment, and with a lower operational cost. This, apparently is a logical solution to the transportation dilema, provided, of course, that an adequate water supply is available.

Figure (3) portrays the geographic situation confronting the steel industry in Northeast India. Steel mills in Jamshedpur, Durgapur, Rourkela, Bokaro, etc., (Table 1) receive raw materials from various isolated sources. For example, iron ore is obtained from the Bonai Iron Range, coal from Raniganj, and the Talchir Coal Field, and limestone from Hathiwadi. The present demands for these supplies range into many millions of tons of each per year and the steel operations are constantly delayed by transportation shortages and are hampered by excessive costs resulting from materials rehandling in changeovers among the various carrier types, including changes in rail gage. The predicted increases in future demands will be even more seriously handicapped. Although the Indian transportation systems are being expanded as rapidly as possible, it is apparent that they will fall short of meeting the increasing industrial demands for many years to come.

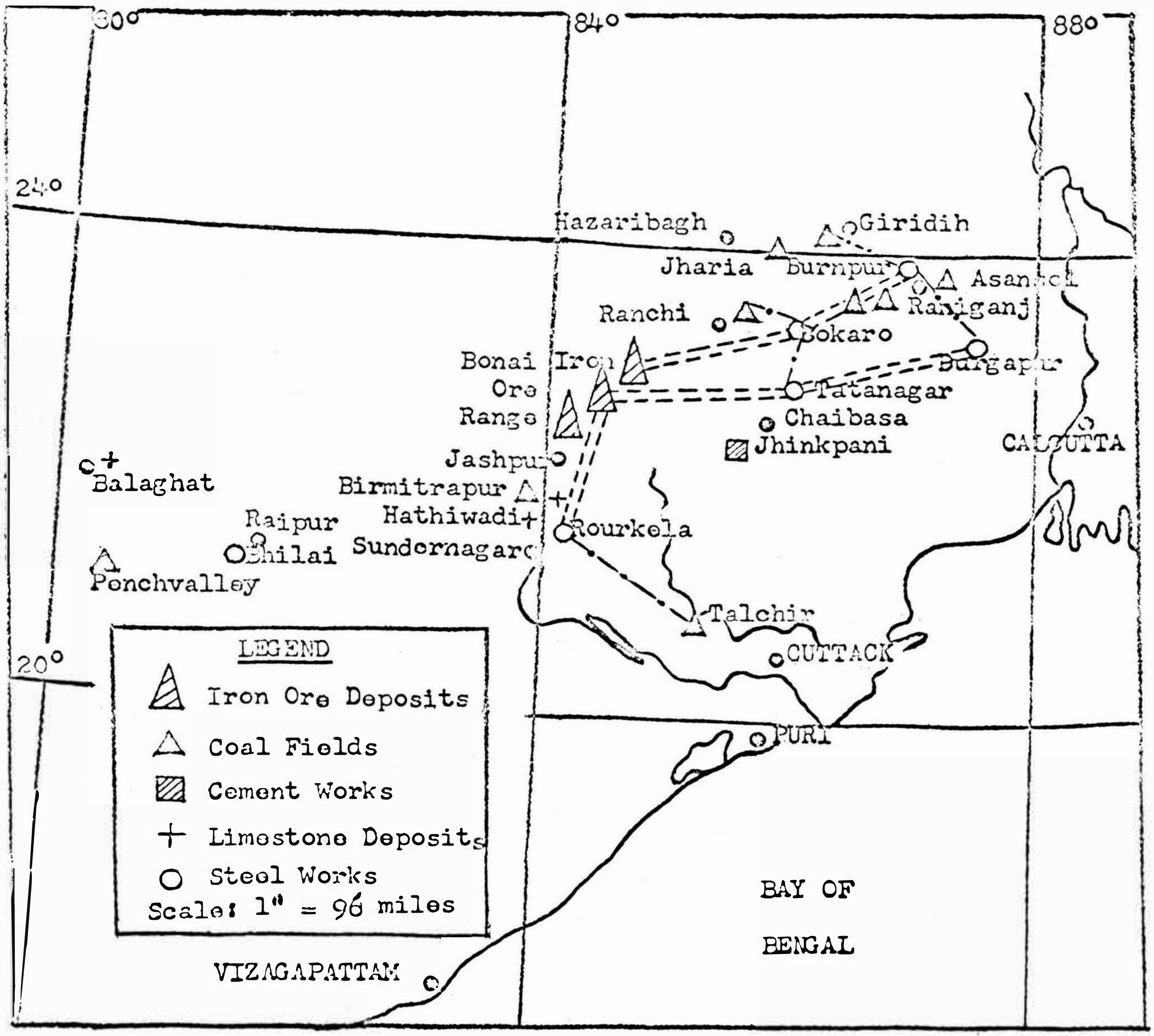

Figure 3. Map of East India Showing Possibilities of Hydraulic Transportation of Raw Materials for Steel Industries

The most direct and undoubtedly the most economical means for overcoming this industrialization bottleneck is the installation of a slurry-pipeline system. An adequate supply of water is available at nearly all production sites, and is not too far distant from the most isolated areas. To further facilitate the movement of materials, all products could be ground at the points of origin according to consumer demands.

TABLE 1

Distribution of Steel Plants and Raw Materials for Steel Industry in India

Steel Plant	Location & Present Production	Raw Material	Location
Tata Iron & Steel Works (Tisco)	Tatanagar	Iron Ore	Noamundi
	2.0 million tons	Coal	Raniganj
		Limestone	Hathiwadi
Indian Iron	Burnpur	Iron Ore	Gua (Bonai Range)
	1.5 million tons	Coal	Asansol
		Limestone	Birmitrapur
Rourkela	Rourkela	Iron Ore	Barsua (Bonai Range)
	1 million tons	Coal	Talchir
		Limestone	Hathiwadi
Durgapur	Durgapur	Iron Ore	Bolani (Bonai Range)
	1 million tons	Coal	Asansol
		Limestone	Birmitrapur

Statement of the Problem

The hydraulic systems of mining and transportation are gradually gaining universal popularity in step with pertinent technological developments. However, considerable research data are still needed in order to develop straightforward, scientifically-based design principles, and especially in open-flume conveying of slurries. For this reason and because of the apparent major importance of slurry transportation to his native land of India, the author chose to investigate some of the factors influencing the flow of slurries into open-flumes as would be experienced in a hydraulic mining operation.

The following parameters were studied and compared with their respective observed behaviors in slurry-pipelines.

1. The effect of particle specific gravity.
2. The effect of particle size.
3. The effect of the solids-water ratio.
4. The effect of flume slope.

REVIEW OF LITERATURE

Hydraulic Mining

As indicated earlier, hydraulic monitors have been used in mining alluvial deposits for more than a century. However, more recent records indicate that the earliest attempts at hydraulicking solid materials were made in Russia, probably in 1935. The results must have been encouraging for, soon after, a research institute was organized to study the hydraulic mining potential.

Apparently, Dr. Muchnik, of the Leningrad Mining Institute, (4) was first to advocate the use of high pressure water jets for underground mining. His first full scale experiment was conducted in the Kizel Coal Basin (Figure 4) during the years 1936 and 1937. This led to the development of a hydraulically operated coal mine in the Donets Basin two years later. (Figure 5)

The next significant advance in hydraulic mining was published in 1956 by Protocyak (4) of Russia. He announced the development of a hardness (hydraulic breakability) scale, ranging from 0.3 for soft soils to 20.0 for hard quartzite and basalt. The details of this scale were not described, however.

A year later (1957) the VNIGidrougol Institute (11,4) reported the following empirical rules which they had formulated

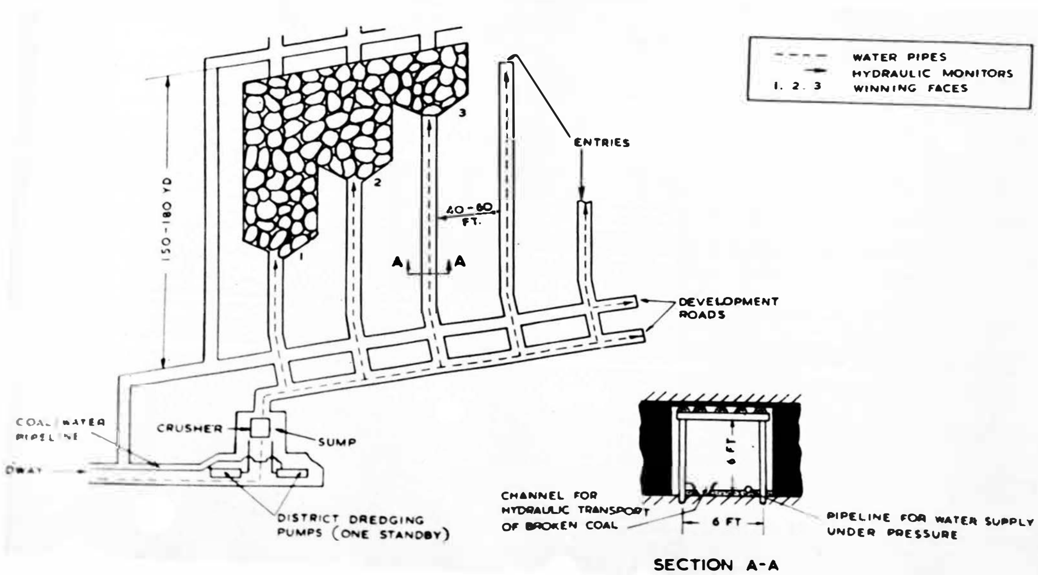

Figure 4. Lay-Out of a Panel for Hydraulic Mining. (11)

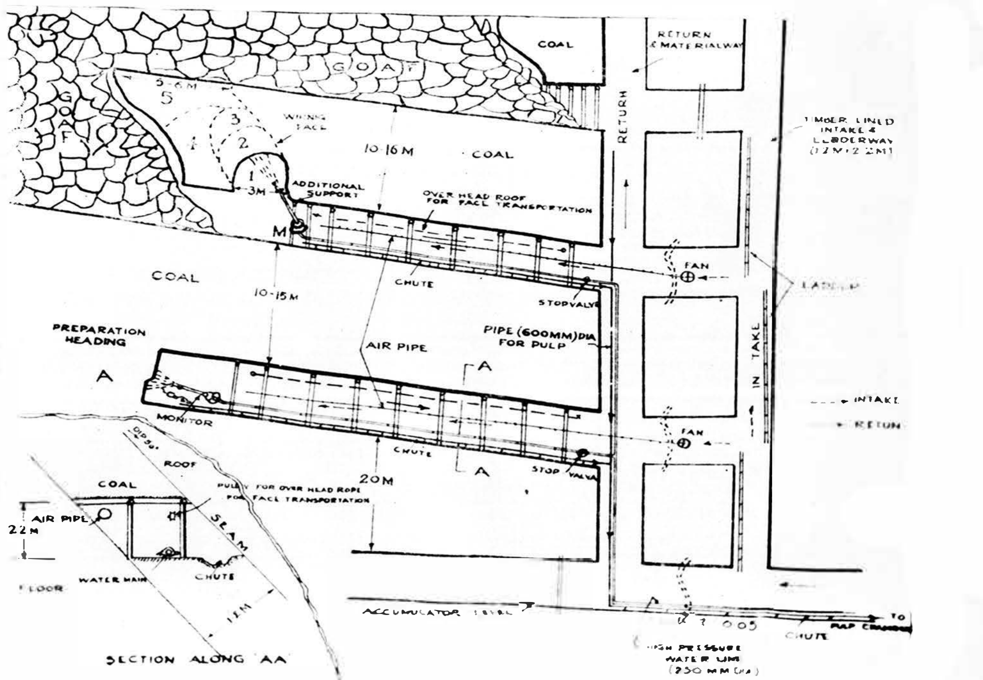

Figure 5. Plan of a Working Panel of a Mine in the Donets Basin. (29)

for designing hydraulic mining equipment:

1. The pressure (Pe) required for effectively breaking coal is determined by

$$Pe = 50 f \text{ atmosphere}$$

Where f = Coal hardness in the Protodyakonov Index

2. The consumption of hydraulic energy (α) required to break one ton of coal is

α = 10 Kwh for solid coal
α = 5 Kwh for fissured coal

3. The energy consumption (E) per ton of coal broken is

$$E = \left(\alpha \frac{P_2}{P_1}\right)^2$$

Where P_2 = Nozzle pressure of the water jet

P_1 = Pressure of the jet at the coal face

4. The monitor capacity (A) in tons of coal broken per hour is

$$A = \frac{QP_2}{36.7\ E} \times K$$

Where Q = Water flow in cubic meters per hour

K = A coefficient assumed at 1.8 for full-face operations and 1.0 for development

Other, extensive research (4) has more recently been reported from Great Britain, France, West Germany, Poland, and Japan.

The first underground hydraulic mining operation in The United States of America (1958) was that of the American Gilsonite Company at Bonanza, Utah (21,28). The company jetted gilsonite from a 22 foot, vertical vein by means of a 3/8-inch nozzle operating under pressures of 2200 psi. (Figure 6).

During the year (1958), The United States Bureau of Mines (24) initiated a series of experiments in mining coal hydraulically from the flat-lying Pittsburgh Bed using water volumes and pressures to 300 gpm and 4000 psi, respectively. The tests were successful and indicated that the technique had potential, especially in pitching beds, where water and mined coal would flow from the face by gravity. Tests were made with nozzles having various internal designs to determine which of these would give the best cutting rate. The most effective results were obtained when the jet stream was held in a solid core.

Wallace, (34) Price, and Ackerman who studied the above operation, have stated that the success of jet mining depended upon several variables; such as water pressure, size and shape of the nozzle used, rate at which the water jet was moved through the coal, depth of cut, and the mining plan. The rate of mining increases as the size of nozzle opening is increased from 1/8 to 1/4 to 3/8 inches, and the rate of mining decreases as the distance from the nozzle to the face increases.

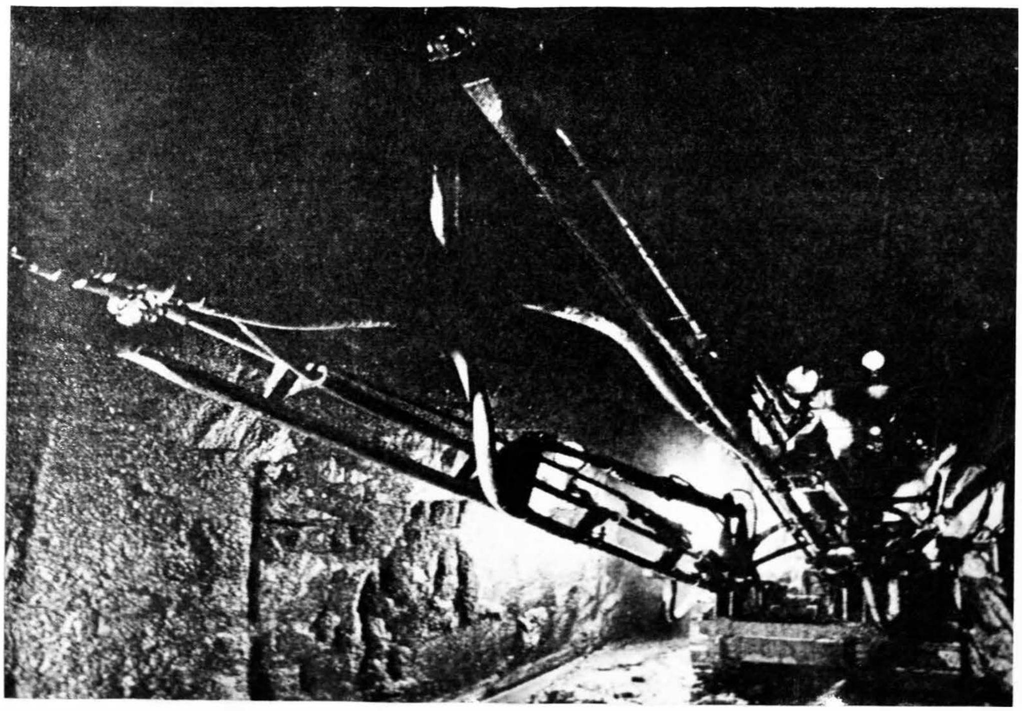

Figure 6. Jumbo Mounted High Pressure Monitors at Bonanza, Utah. (21, 28)

A Russian (4) article (1959) reports that the output of one mining installation reached 44 tons per man shift after four years of hydaulic mining, and the percentage recovery was about 87 percent. Other sources report that, after several years of operation, monthly production was two and one half to three times greater than the monthly output of the most productive deep mines in the same area, and the production costs were about equal to the cost of strip mining in the same area.

In 1961, The United States Bureau of Mines (6) found the hydraulic productivity, in tons per man-shift, to be about 25 percent higher when compared to conventional mining in the same area. A year later, McMillan (20) made a complete study of more recent data and concluded that the average hydraulic productivity exceeded the local conventional average by 50 percent (See Table 2).

The Black Knight (30) Mine (1962), of Coal Inc., Ravensec, Washington was the first company in the United States to start hydraulic coal mining on a commercial basis. The coal was mined by high pressure monitors from a longwall face in seams pitching to 72 degrees.

Buch and Williams (5) (1962) describe the experiments carried out at the Sugar Notch Mine, Wilkes-Barre, Pennsylvania. This project was carried out by The United States Bureau of Mines in cooperation with the Glen Alden Coal Company. The anthracite was mined hydraulically, using 300 gpm of water at 5000 psi pressure (Figure 7).

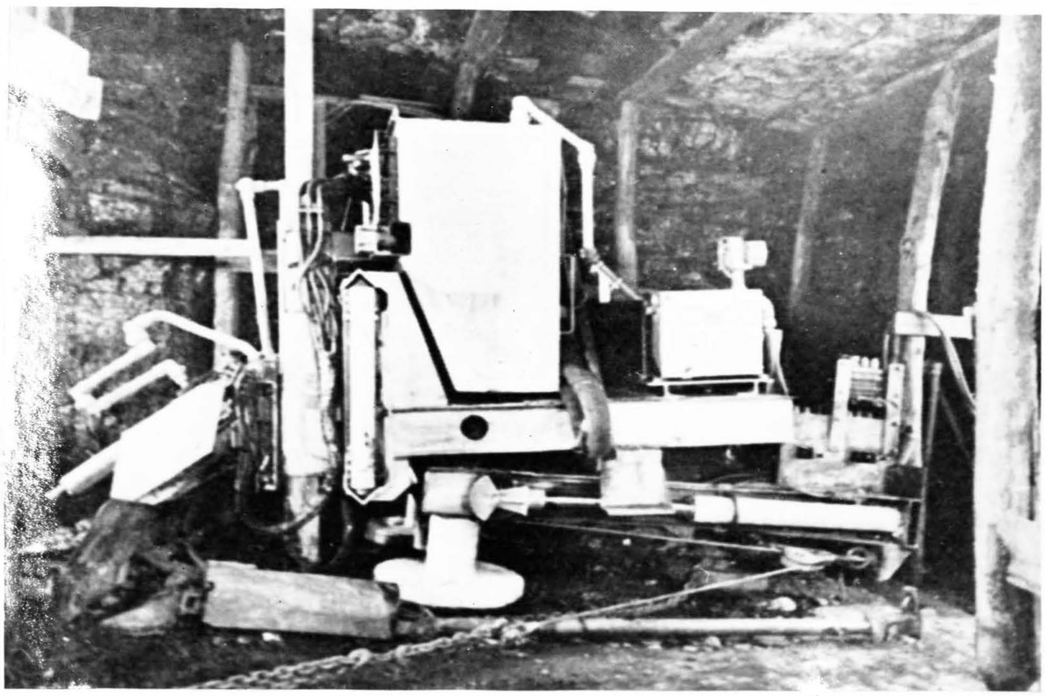

Figure 7. Monitor used by the U.S. Bureau of Mines at the Sugar Notch Anthracite Mine. (5)

TABLE 2

Average Productivity of Experimental

Hydraulic Jet Mining (20)

Month	Tons Produced	Tons per Man Shift	Jetting Time per Shift Minutes	Tons per Minute of Jetting
1961				
Sept.*	702	16.7	157	0.45
Oct.	1392	12.7	142	0.45
Nov.	1370	13.7	173	0.41
Dec.	1253	15.5	139	0.57
1962				
Jan	1135	14.2	127	0.82
Feb.	1982	19.8	128	0.72
March	1610	15.3	116	0.70
Average	1349	15.4	141	0.59

*Last half of month

Nasiatka and Badda (24) (1963) have described the tests conducted with high pressure water jets, at Roslyn, Washington. They concluded that, in pillar mining and using a hand held monitor, the best results were obtained with a 0.150 inch diameter nozzle, a water pressure of 3500 pai, and a flow rate of 38.5 gpm. The rate of mining and productivity were 0.74 tons per minute and 16.6 tons per man shift, respectively. Tests also showed that hydraulic methods were more productive than the conventional techniques in pillar mining whereas, in development, the productivity depended primarily upon coal hardness.

Integrated Hydraulic Mining and Transportation

Peat was mined and flumed hydraulically in Russia since 1918 (4), and in 1928, hydraulic equipment was installed at a brown coal open-pit mine to remove overburden. These operations apparently were successful, and yet the use of high-pressure water jets for breaking solid coal was not considered until 1935 due to the lack of suitable equipment.

The New Zealand States, Mining Department (1959), states (4) that hydraulicking was used by a local operator to extract coal and remove overburden since 1891. The broken coal was transported to the point of consumption in open flumes. This operation was in a remote area, and therefore the advantages of this novel means of coal mining and transportation remained unnoticed by the coal industry of New Zealand until 1920. In that year, a coal mining company constructed a 1/4 mile outdoor flume to move their coal from the mine to the main road. This flume proved to be so profitable, that the following year its length was extended to 3 miles. The coal mining industry of the immediate area was so highly impressed by the project's economy that the following year, two additional coal companies built flumes to transport their coal in a like manner.

After his earlier successes in hydraulic mining, Dr. Muchnik (4)

designed a gravity flow system for a coal mine in the Donets Basin. All entries were developed on a 5 percent grade so as to permit the coal slurries to move to the shaft bottom along a system of drain ditches.

The American Gilsonite Company (21,28) installed a complete hydraulic transportation system for their mine in Utah. The gilsonite was collected in a sump through a network of steel flumes and then pumped through 72 miles of 6-inch diameter pipe (Figure 8) to their treating plant at Grand Junction.

Mercer (1960) describes hydraulic stripping (Figure 9) of a British Guiana (19) bauxite deposit. The mine is operated by the Demerara Bauxite Co.Ltd. The ore is overlain by 50 to 180 feet of loose silica and clay which is removed hydraulically by 8000 gpm of water at pressures of 60 to 100 psi. The overburden is monitored into a huge sump, from where it is transferred through 5500 feet of pipe at the rate of 300 to 400 cu. yds. per hr. The Intelli-Giant hydraulic monitors are positioned laterally and vertically by remote control. The success of this operation is attested by an initial savings of 50 percent over their previous method.

An efficient, rubber lined tailing flume (1963) has been constructed by the Iron Ore Company of Canada, (3) at Labrador City (Figure 10). The flume is nine feet in diameter, 3,367 feet long, and disposes 50,000 gallons of tailings per minute.

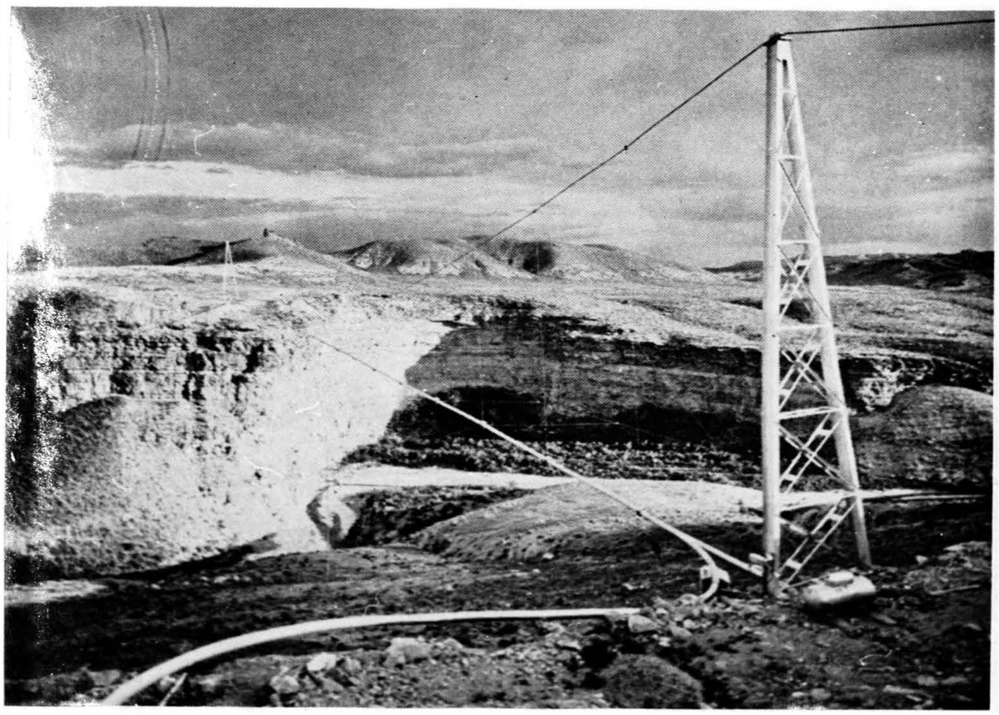

Figure 8. Six-inch Gilsonite Pipeline of American Gilsonite Company, Crossing a Canyon. (21)

Figure 9. Hydraulicking of Sand and Clay Overburden for Mining Bauxite (19)

Figure 10. Flume Disposing 50,000 Gallons of Tailings per Minute at Labrador City. (3)

Hydraulic Transportation

Fluming

Reddy (1963) summarizes (25) the current status of open-flume transportation and reports the findings resulting from his studies of coal-water flow in outdoor steel flumes. He concludes that it is possible to transport (-) 1/2-in. coal, in a 40 percent (by weight) concentration, at the rate of 4.15 fps and on a (-) 4.0 percent slope.

Flume Design:

The flow-rates of slurries in open channels can be calculated with reasonable accuracy from the Chezy-Manning equation as given by Vennard (32) and in which

$$Q = \frac{1.49}{n} \cdot AR^{2/3} S^{1/2}$$

Where Q = Discharge in cubic feet per second

A = Area of channel cross section in square feet

n = Manning's coefficient

S = Bottom slope in percent

R = Hydraulic radius in feet

It is evident that, for any given conditions of flow-area (A), slope (S) and roughness (n), the rate of uniform flow (Q) through a flume will be maximum when the hydraulic radius (R)

is maximum. Therefore, it is important for economic reasons to keep the dimensions of the cross section such that the maximum hydraulic radius will result. From the definition of hydraulic radius, $R = A/P$, it can be seen that a cross section of maximum hydraulic radius is one of minumum wetted perimeter (P).

A circular pipe satisfies the above conditions most effectively. However, other shapes may be dictated by usage and / or construction and maintenance costs. In such cases, the cross-sectional dimensions should be proportioned so as to produce the most beneficial ratios. For example, in considering the following shapes in the order of decreasing efficiency:

1. A semi-circular channel will have the depth of flow equal to its radius.
2. A trapezoidal flume will have a hydraulic radius equal to one-half its depth of flow.
3. A rectangular trough will have a depth of flow equal to one-half its width.

The dimensions of other shapes can likewise be balanced mathematically.

Hoisting

The SOGREAH Company of France (8,9) has done extensive research in hydraulic hoisting at the Devillaine coal mine near St. Etienne. The pilot installation has been in operation since 1960 and has since proved to be entirely satisfactory. Its capacity is 50 to 60 tph with a 60 percent concentration of minus $3\frac{1}{4}$-in. coal. The hoisting height is 590 feet and with 215 feet of horizontal pipeline.

Cockerill (2) describes an ore slurry pumping operation of the Bancroft Mines, Northern Rhodesia where the ore body consists of copper bearing siltstone, part of which is reduced to a soft friable clay. The underground water turns this clay into heavy and uncontrollable mud. The problem was solved by hydraulic hoisting through a system which is capable of moving a 40 percent concentration of (-) 3/16-inch material at the rate of 157 tph. Nine pumps are coupled in series at the 1317-foot and 650-foot levels to generate the necessary pressures. Pumps on the 1317-foot level convey the material into the open sump on 650-foot level, from where it is pumped to the surface.

Unisearch Ltd, (1) a subsidiary of the University of New South Wales patented a hydraulic hoist which will be able to handle large size solids and with a high solids-liquid ratio. This process is known as "Hydro-Lift" and is claimed to be capable

of lifting solids at very high capacities and at low velocities. A twenty-four-inch line will convey coal at about 1000 tph, with the top size of solids conveyed at 50 percent to 75 percent of the line diameter and with a preferred solids-liquid ratio between 1:1.5 and 1.5:1. Because such large solids can be transported, the crushing costs at the source and dewatering costs at the destination can be minimized. Several sizes and types of solids can be transported as a mixture and then separated at the terminal.

Pipelining

Lewin (17) and Koch (16) describe and outline the important factors to be considered in the design of slurry pipelines, and Nardi (22,23) stresses the influence of the physical properties of solids and slurries upon pipeline performance. Durand and Condolios (14), after extensive research, have classified slurry flow according to the size of solid particles and have proposed a group of regimes with appropriate empirical rules predicting the slurry behaviour for each flow condition.

Durand (14) compiled extensive data concerning pipeline slurries from which he developed an empirical expression for the minimum velocity (V_L) required for flushing uniform-size solids through a horizontal pipe without causing stationary deposition in the line, in which

$$V_L = F_L \sqrt{2gD \frac{\rho' - \rho}{\rho}}$$

Where, D = Pipe diameter, g = Acceleration due to gravity

ρ = Mass per unit volume of water

ρ' = Mass per unit volume of solids

F_L= A constant, depending upon concentration and size of solids

The classification and experimental relationships given by Durand remain valid for solids of any specific gravity, provided that the appropriate values are considered.

Because the mechanisms of fluid motion are similar in pipes and open channels, it can be assumed (31) that the hydraulic radius concept will account adequately for the differences in the cross sectional shapes of circular pipes and flumes and that the above equation can be used for flumes by replacing D with 4R, (32) where R = A/P. To check its validity, the following experimental data, produced by Reddy (25), are inserted into the formula:

Depth of flow = 1.845

Concentration = 40% coal, 60% water

Size = -1/2"-0

Slope = 4%

F_L = 1.34 (From Durand's Graph)

ρ' = 1.32

$$\text{Area} = \frac{5.81 + 4}{2} \times 1.845 = 4.90 \times 1.845 = 9.08 \text{ in}^2$$

Wetted perimeter = 4 + 2.01 + 2.01
= 8.02-in.

$$R = A/P = \frac{9.08}{8.02} = 1.13\text{-in.}$$

$$\frac{V_L}{\sqrt{2gD\,\frac{\rho' - \rho}{\rho}}} = F_L$$

$$V_L = F_L \sqrt{2gD\,\frac{\rho' - \rho}{\rho}}$$

$$= 1.34\sqrt{2 \times 32.2 \times \frac{4 \times 1.13}{12} \times .32}$$

$$= 2.79 \times 1.34 = 3.72 \text{ fps (critical velocity)}$$

This is somewhat lower than the 4.15 fps (critical-velocity) recorded by Reddy. However, close scrutiny of the graph from which Reddy derived his interpolated value will reveal that the experimental and theoretical critical velocities could be equal. It is therefore assumed that Durand's empirical formula for pipelines can be applied with equal accuracy to the flow slurries in open flumes.

Constantini (12) quite completely analyzes the factors that influence the efficiency of slurry pipelines and predicts a promising future for the method. His beliefs are strongly verified by various new and extensive pipeline systems being proposed in many parts of the world.

A $56 million line (10) is being planned to extend 900 miles from Southern Rhodesia to Southwest Africa to transport 3 million tons of coal per year. Another (10) $28 million pipeline will move coal from the Ishikari Coal Field to Tomakomai, Japan, and supposedly reduce shipping costs from the present $5.13 per ton to about $2.50 per ton. A Canadian (7) firm is planning to move millions of tons of sulphur, coal, and gypsum through a 740 mile network of pipes whose diameters will range from 8 to 20 inches. Poland (10) is seriously considering a $500 million project to convey 8 million metric tons of coal from the Silesian Coal Field to a mill at Nova Hutta. Other examples of successful and proposed pipelines are summarized by Reddy. (25)

The economics of pipelines have been studied by Thagard (10) and Reichl (10) with very favorable results. A Russian (22) installation is reported to have operated since 1957 at one-third the cost of rail haulage. Other, similar examples are cited by Riggs (27) (Figure 11), Berkowitz (3) (Figures 12 and 13), and Reddy. (25)

The U.S. Department of Interior formed a Panel on Civilian Technology which studied (26) the technical and economic feasibility of slurry pipelines. They investigated a hypothetical line that extended from Virginia to the Baltimore-New York area

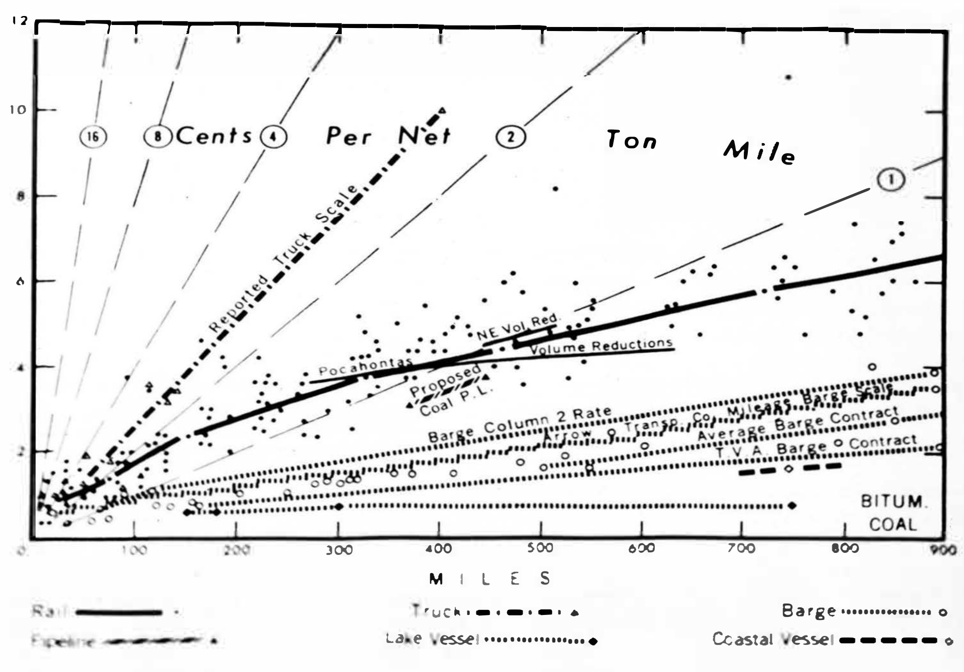

Figure 11. Freight Revenue and Mileage Comparisons for Various Modes of Transportation for Bituminous Coal. (27)

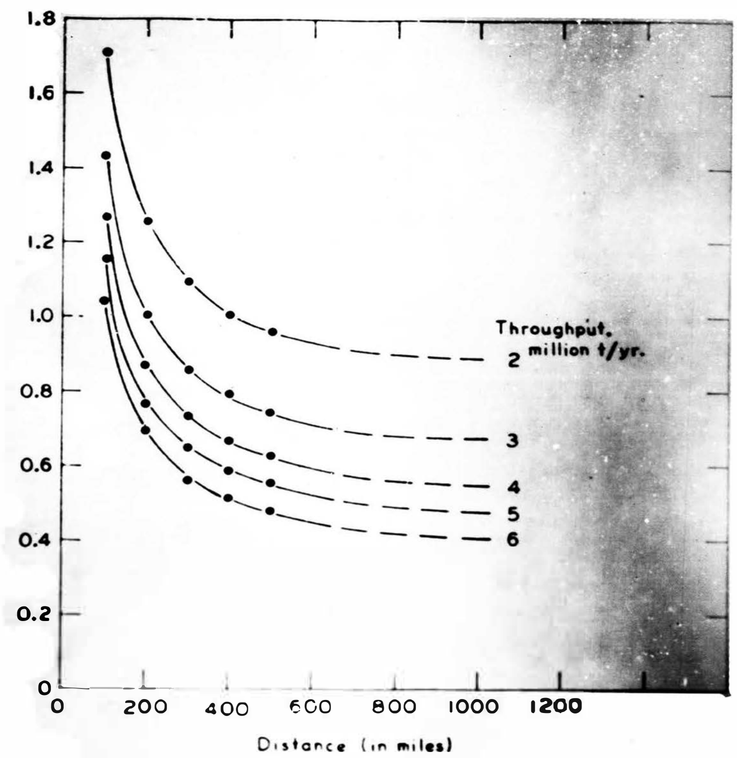

Figure 12. Preparation and Transmission Costs for 60:40 Aqueous Slurries as a Function of Distance and Annual Throughput. (3)

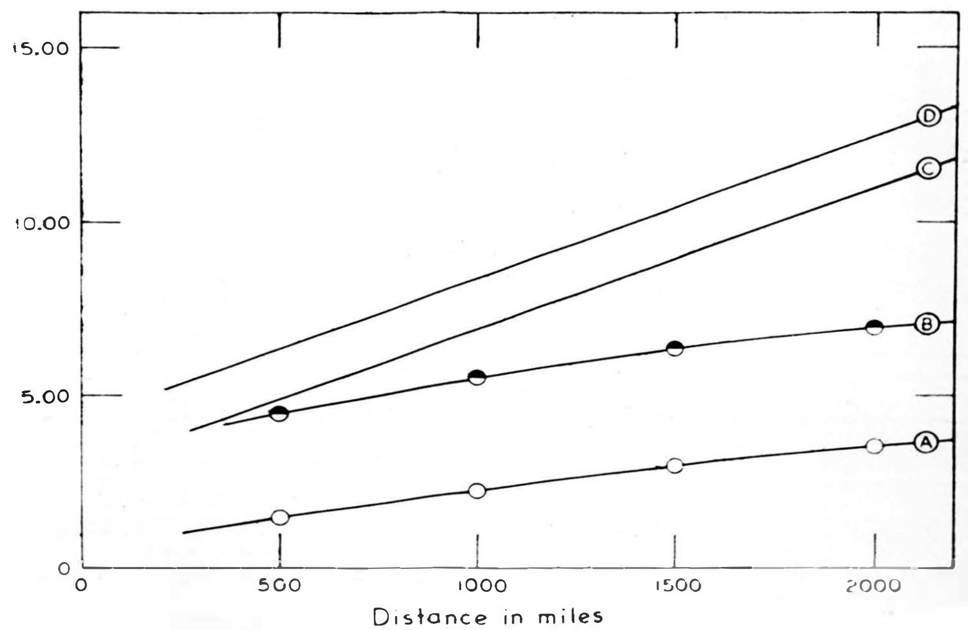

Figure 13. Estimated Transportation Costs:

A. Pipelined Oil

B. Pipelined Coal

C. Current Canadian Long Distance Railway Freight Charges

D. Railway Transported Coal (3)

in order to determine the most suitable and economical means of provinding electricity at the destination from coal at the mines. This included transportation, storage, preparation and utilization of the product. Of the four transport methods studied (high-voltage transmission, modern railroad, conveyor belt, and pipeline) the pipeline was chosen as being the most advantageous. A recent reduction in railroad transportation charges will alter these findings to some extent.

LABORATORY INVESTIGATIONS

Purpose

The purpose of this research was to investigate the effects of particle specific gravity, particle size, solids-water ratio, and flume slope upon the ease with which mine products can be flushed into an open-flume and conveyed therein without subsequent deposition. It was intended to partially simulate the slurry flow conditions that would result from hydraulic mining and thereby contribute some basic knowledge which may be helpful in future designs of such systems.

A series of tests were conducted with the available sizes of coal, limestone, and hematite to determine the minimum water volumes required to flush the solids into a uniform flow pattern on 4.0 percent and 5.5 percent flume slopes.

Equipment

The equipment used in conducting flow tests is shown in Figure (14). It consists of a steel tank for water volume control, a flexible steel pipe for flow rate control, and an inclined steel trough for flow characteristic studies. The steel tank, 30-inch diameter by 30-inch high, was mounted on a timber trestle as shown in the figure. A 5-inch diameter flexible steel hose was welded to a lower side of the tank with its loose end held vertically, when not in use by means of a rope pulley arrangement. The trapezoidal

Figure 14. The Tank, Flexible Pipe and Flume with Supporting Structure

steel trough was 4 inches wide at the bottom, 13 inches across the top, and 9 inches deep. It was composed of 5 sections, each 12 feet long, and provided with vertically adjustable supports that permitted flume slope variation to maximum of 6 percent.

Additional equipment was used for sample preparation, slope determinations, velocity measurements, etc. The more important of these included a vibrating screen (Figure 15), a water-volume meter (Figure 16), an engineer's transit, a jolly balance and stop-watch.

Sample Preparation

Samples of coal, limestone, and hematite, were separately hand-crushed and screened to the following size fractions (see also Figures 17, 18, 19, and 20).

Fines-	0-1/16-in.
Medium fines-	1/16-1/4-in.
Medium coarse-	1/4-5/8-in.
Coarse-	5/8-1 1/8-in.

A number of samples, weighing about 100 grams each, were taken from each size fraction and tested for specific gravity by the standard Jolly Balance method. The results were then averaged (Table 3) for each mineral group to provide a representative value for future calculations.

Figure 15. The Vibrating Screen

Figure 16. The Water Meter

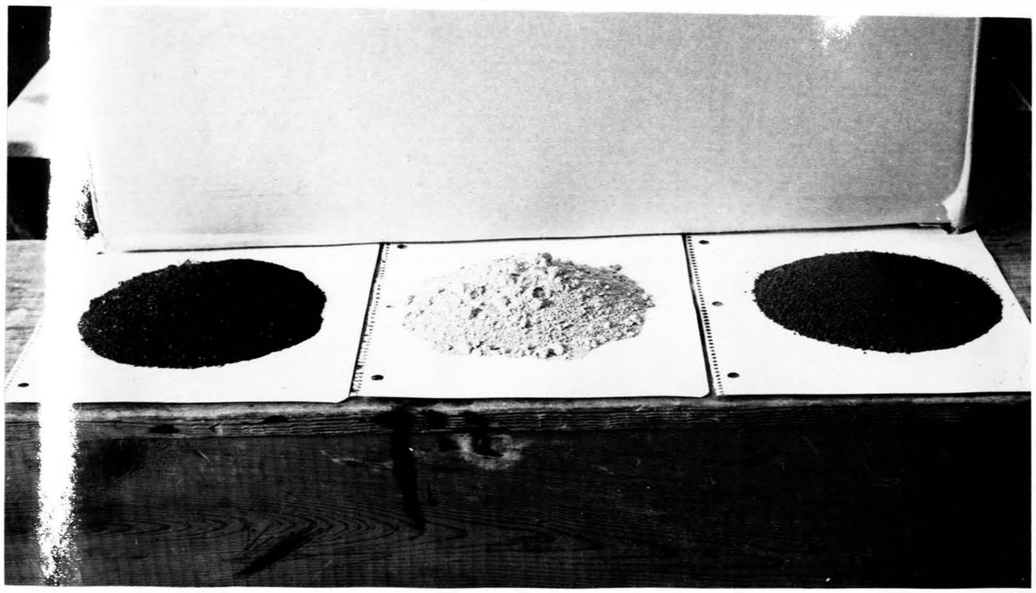

Figure 17. Samples of 0-1/16-in. Size; Coal, Limestone, and Hematite.

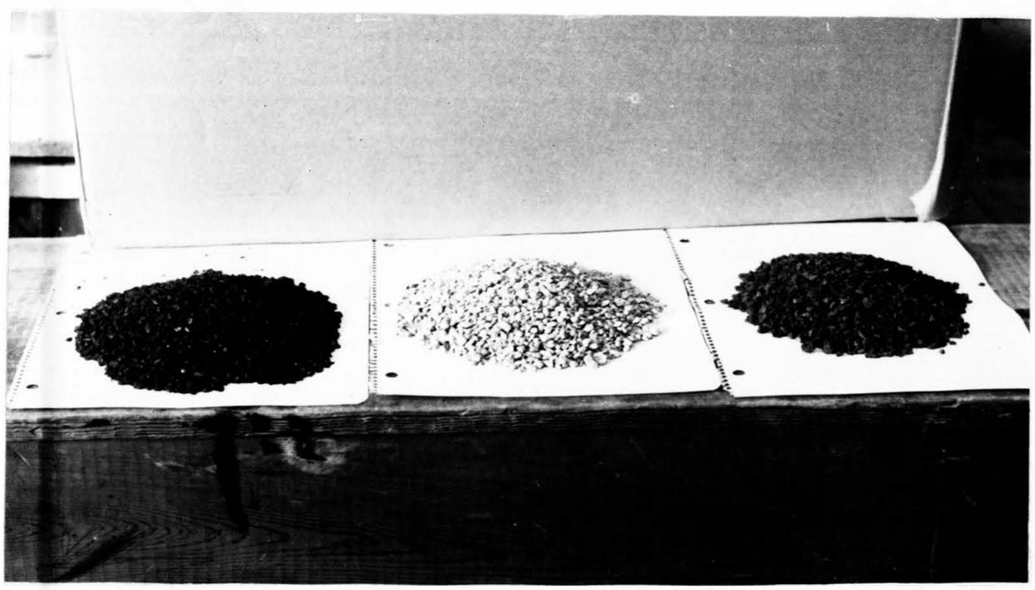

Figure 18. Samples of 1/16-1/4-in. Size; Coal, Limestone, and Hematite.

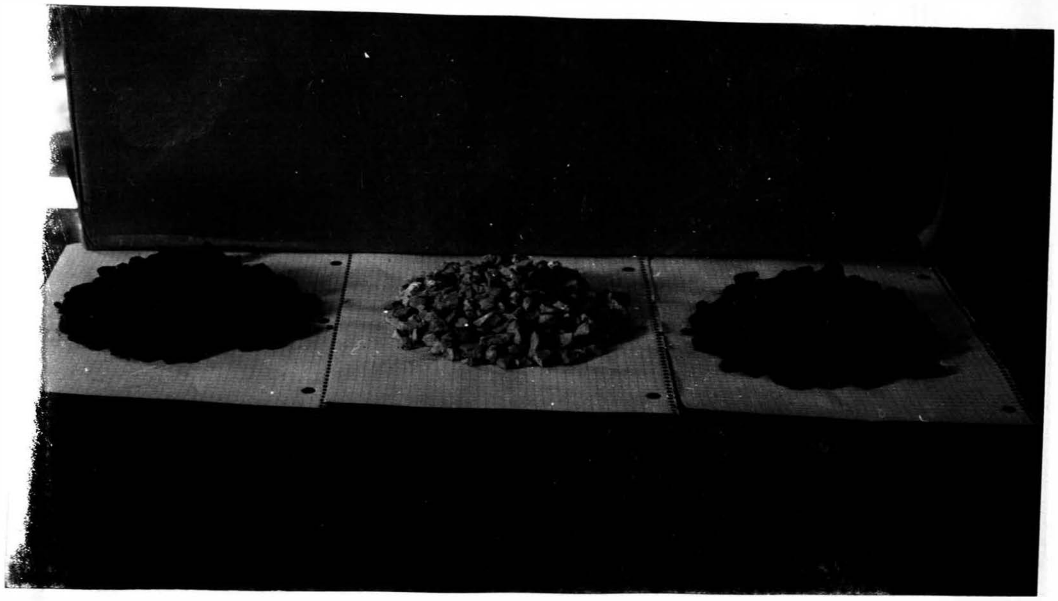

Figure 19. Samples of 1/4-5/8-in. Size; Coal, Limestone, and Hematite.

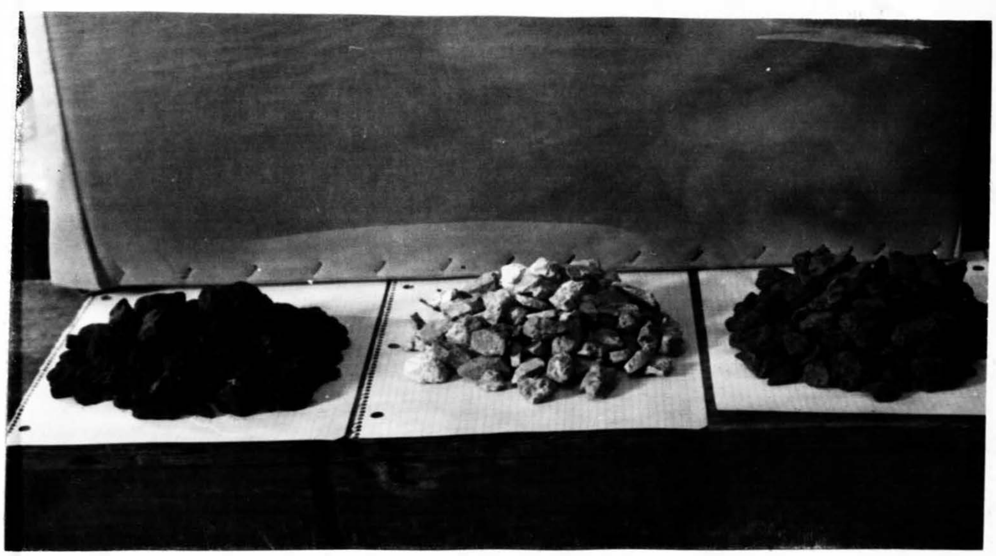

Figure 20. Samples of 5/8-1 1/8-in. Size; Coal, Limestone, and Hematite.

TABLE 3

Specific Gravity of Coal, Limestone, and Hematite.

Material	I	II	III	IV	Total	Average Sp.Gravity
Coal	1.241	1.298	1.263	1.270	5.072	1.27
Limestone	2.599	2.738	2.642	2.697	10.676	2.67
Hematite	4.459	4.815	3.602	3.287	16.163	4.04

Procedure

Samples of the solid materials were each, in turn, dispersed within the upper 12 feet of trough and flushed with clear water from the flexible tube and with the tank acting as a reservoir. A minimum rate of water flow would be continued until all of the solids became water borne and were thus carried through the discharge end of the flume. Trial time and water consumption were measured and used in calculating water requirements, in gpm, to carry the solids in tph.

The solids were rescreened after each test and stored for future use. The coal showed very little size reduction whereas the limestone and hematite suffered almost none. In all cases,

the degradation was roughly proportional to particle toughness.

Results

The resulting test data are compiled in Tables 4 through 14 and represented graphically in Figures 21 through 45. Figures 21 through 23 and 24 through 26 show the "Effects of Particle Size upon Slurry Flow" on 5.5 and 4.0 percent flume slopes, respectively; Figures 27 through 30 and 31 through 34 portray the "Effects of Particle Specific Gravity upon Slurry Flow" on similar respective slopes; and Figures 35 through 38, 39 through 42 and 43 through 45 indicate the "Effects of Flume Slope upon Slurry Flow" respectively for coal, limestone and hematite.

TABLE 4

Weight of Solids Transported in Relation to Water Flow and Gradient

Material: Coal

Sp.Gr: 1.27

Size: 0-1/16-in.

Test No.	Slope Percent	Water Required gpm	Solids Transported tph
1	5.5	13.8	1.13
2	5.5	16.9	1.39
3	5.5	18.85	1.64
4	5.5	19.45	1.71
5	5.5	23.6	2.10
6	5.5	27.5	2.40
7	4.0	18.5	0.346
8	4.0	19.4	0.45
9	4.0	20.4	0.563
10	4.0	29.0	1.07

TABLE 5

Weight of Solids Transported in Relation to

Water Flow and Gradient

Material: Coal

Sp.Gr: 1.27

Size: 1/16-1/4-in.

Test No.	Slope Percent	Water Required gpm	Solids Transported tph
1	5.5	9.27	0.538
2	5.5	9.55	0.819
3	5.5	10.60	1.16
4	5.5	11.9	1.25
5	5.5	13.2	1.20
6	5.5	13.8	1.49
7	5.5	17.63	1.80
8	4.0	19.60	0.693
9	4.0	20.90	0.836
10	4.0	21.5	1.09
11	4.0	30.4	1.52
12	4.0	31.0	1.54

TABLE 6

Weight of Solids Transported in Relation to

Water Flow and Gradient

Material: Coal

Sp.Gr: 1.27

Size: 1/4-5/8-in.

Test No.	Slope Percent	Water Required gpm	Solids Transported tph
1	5.5	14.3	0.72
2	5.5	16.0	0.96
3	5.5	17.7	1.51
4	5.5	21.6	1.70
5	5.5	22.7	1.90
6	5.5	28.2	2.51
7	4.0	17.6	0.79
8	4.0	18.0	0.805
9	4.0	23.4	0.71
10	4.0	24.0	1.02
11	4.0	27.1	1.36

TABLE 7

Weight of Solids Transported in Relation to

Water Flow and Gradient

Material: Coal

Sp.Gr: 1.27

Size: 5/8-1 1/8-in.

Test No.	Slope Percent	Water Required gpm	Solids Transported tph
1	5.5	23.30	1.09
2	5.5	28.0	2.85
3	5.5	32.60	1.94
4	5.5	39.60	2.40
5	5.5	52.30	3.42
6	5.5	89.0	5.05
7	5.5	116.0	7.75
8	4.0	15.56	0.50
9	4.0	16.70	1.28
10	4.0	17.10	0.776
11	4.0	20.20	1.15
12	4.0	50.20	2.50

TABLE 8

Weight of Solids Transported in Relation to

Water Flow and Gradient

Material: Limestone

Sp.Gr: 2.67

Size: 0-1/16-in.

Test No.	Slope Percent	Water Required gpm	Solids Transported tph
1	5.5	9.5	0.308
2	5.5	12.6	0.422
3	5.5	13.30	0.45
4	5.5	14.50	0.565
5	5.5	14.62	0.53
6	4.0	15.50	0.179
7	4.0	21.80	0.267
8	4.0	22.60	0.414
9	4.0	29.20	0.584

TABLE 9

Weight of Solids Transported in Relation to

Water Flow and Gradient

Material: Limestone

Sp.Gr: 2.67

Size: 1/16-1/4-in.

Test No.	Slope Percent	Water Required gpm	Solids Transported tph
1	5.5	20.1	0.338
2	5.5	24.1	0.442
3	5.5	26.2	0.535
4	5.5	31.3	0.647
5	5.5	38.4	0.90
6	5.5	39.2	0.89
7	5.5	41.1	0.91
8	5.5	59.5	1.285
9	4.0	21.8	0.206
10	4.0	29.7	0.281
11	4.0	39.1	0.435
12	4.0	45.6	0.517
13	4.0	53.5	0.570

TABLE 10

Weight of Solids Transported in Relation to

Water Flow and Gradient

Material: Limestone

Sp.Gr: 2.67

Size: 1/4-5/8-in.

Test No.	Slope Percent	Water Required gpm	Solids Transported tph
1	5.5	15.98	0.274
2	5.5	20.40	0.308
3	5.5	24.30	0.321
4	5.5	24.90	0.394
5	5.5	30.90	0.460
6	5.5	34.05	0.490
7	5.5	35.80	0.540
8	5.5	39.50	0.584
9	5.5	47.70	0.772
10	4.0	13.20	0.125
11	4.0	18.70	0.258
12	4.0	27.60	0.371
13	4.0	31.30	0.415

TABLE 10 (Continued)

Test No.	Slope Percent	Water Required gpm	Solids Transported tph
14	4.0	32.0	0.383
15	4.0	36.2	0.416

TABLE 11

Weight of Solids Transported in Relation to

Water Flow and Gradient

Material: Limestone

Sp.Gr: 2.67

Size: 5/8-1 1/8-in.

Test No.	Slope Percent	Water Required gpm	Solids Transported tph
1	5.5	24.0	0.272
2	5.5	74.0	0.930
3	5.5	57.9	0.807
4	5.5	81.5	1.0
5	5.5	105.0	1.33
6	5.5	126.0	1.72
7	5.5	138.5	1.60
8	5.5	147.0	1.80
9	4.0	24.7	0.205
10	4.0	42.2	0.410
11	4.0	52.9	0.566
12	4.0	53.0	0.565

TABLE 11 (Continued)

Test No.	Slope Percent	Water Required gpm	Solids Transported tph
13	4.0	61.5	0.535

TABLE 12

Weight of Solids Transported in Relation to

Water Flow and Gradient

Material: Hematite

Sp.Gr: 4.04

Size: 0-1/16-in.

Test No.	Slope Percent	Water Required gpm	Solids Transported tph
1	5.5	5.98	0.088
2			
2	5.5	9.40	0.168
3	5.5	12.30	0.268
4	5.5	12.40	0.230
5	5.5	12.45	0.218
6	5.5	12.50	0.205
7	4.0	23.10	0.233
8	4.0	26.0	0.260
9	4.0	26.2	0.183
10	4.0	27.3	0.281
11	4.0	31.0	0.225

TABLE 13

Weight of Solids Transported in Relation to

Water Flow and Gradient

Material: Hematite

Sp.Gr: 4.04

Size: 1/16-1/4-in.

Test No.	Slope Percent	Water Required gpm	Solids Transported tph
1	5.5	11.75	0.116
2	5.5	14.05	0.136
3	5.5	16.35	0.156
4	5.5	16.60	0.154
5	5.5	17.60	0.203
6	5.5	19.05	0.208
7	4.0	25.40	0.164
8	4.0	28.10	0.177
9	4.0	39.60	0.255
10	4.0	45.70	0.326

TABLE 14

Weight of Solids Transported in Relation to

Water Flow and Gradient

Material: Hematite

Sp.Gr: 4.04

Size: 1/4-5/8-in.

Test No.	Slope Percent	Water Required gpm	Solids Transported tph
1	5.5	30.0	0.2
2	5.5	37.8	0.284
3	5.5	45.2	0.30
4	5.5	46.25	0.31
5	5.5	48.60	0.36
6	5.5	52.20	0.341
7	5.5	60.07	0.36
8	4.0	23.4	0.153
9	4.0	36.0	0.291
10	4.0	42.2	0.271
11	4.0	36.6	0.251

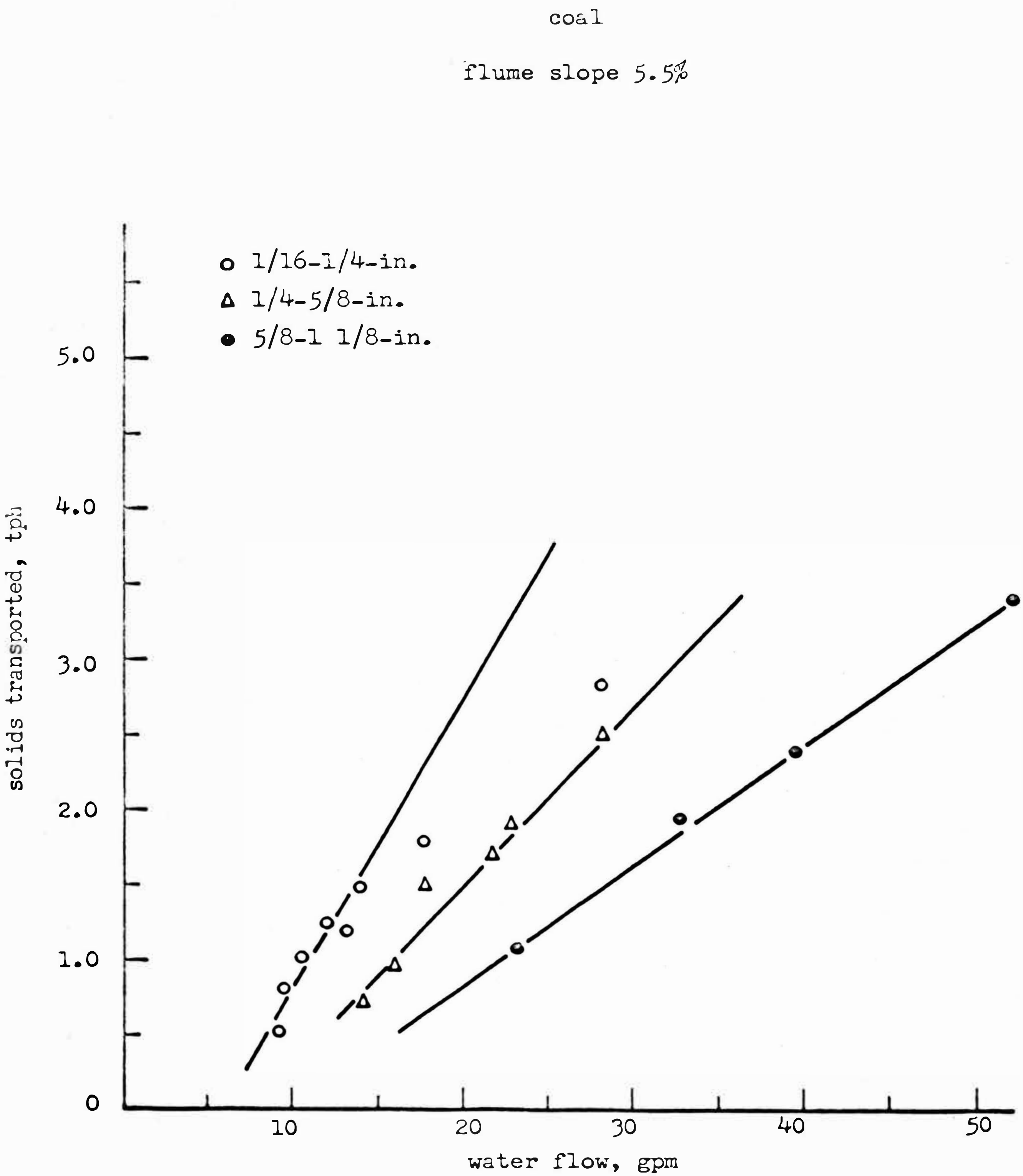

Figure 21. Effects of Particle Size upon

Slurry Flow

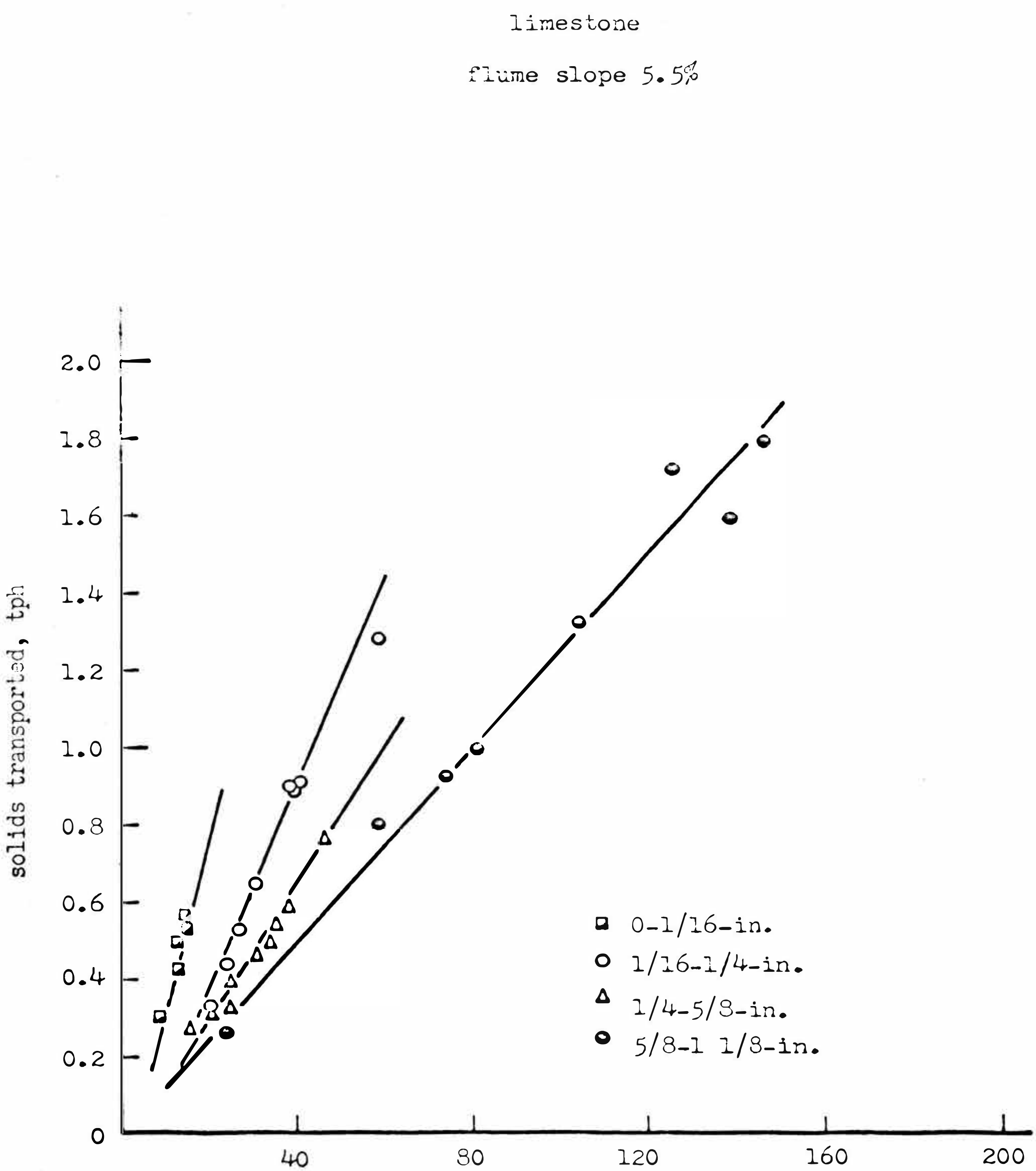

Figure 22. Effects of Particle Size upon

Slurry Flow

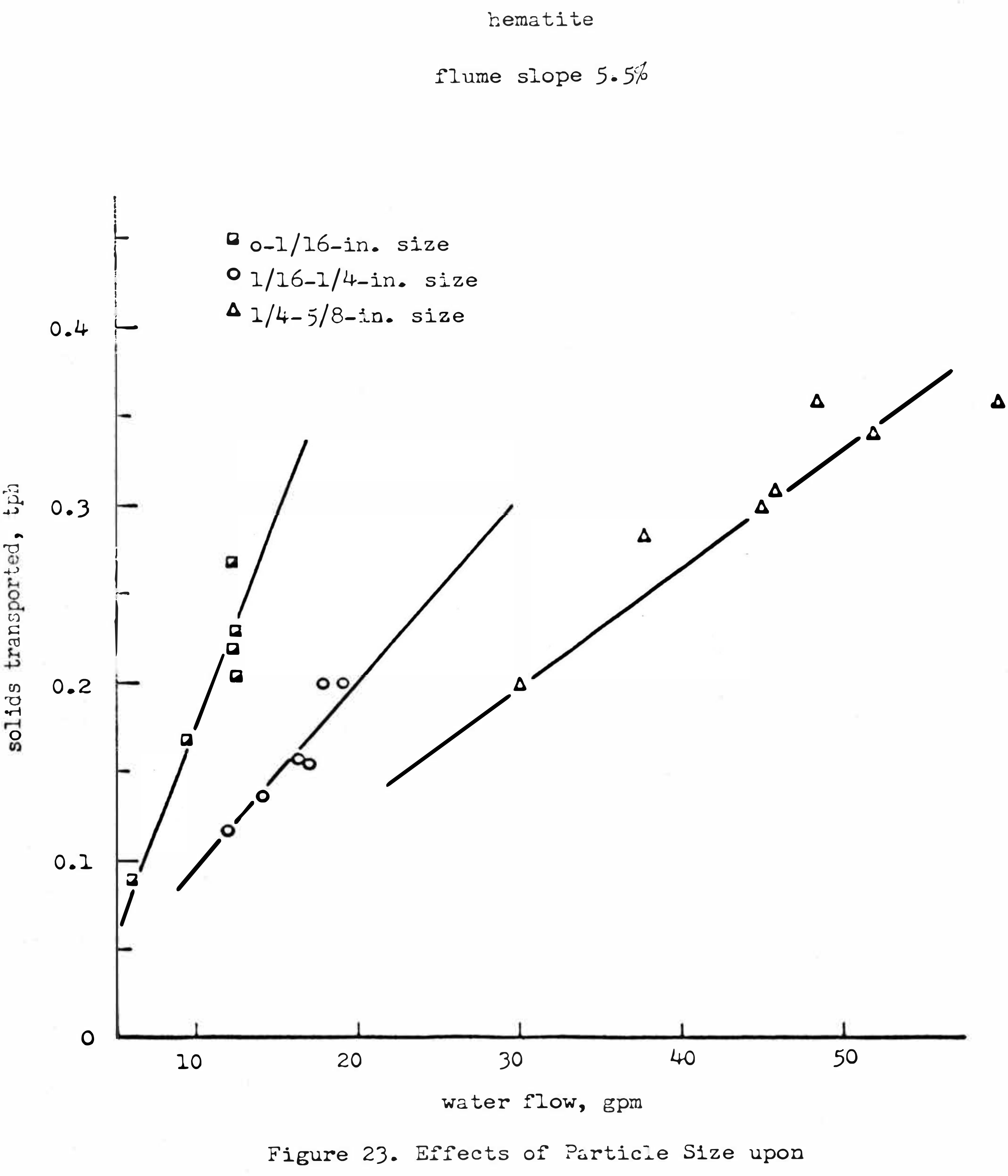

Figure 23. Effects of Particle Size upon Slurry Flow

coal

flume slope 4.0%

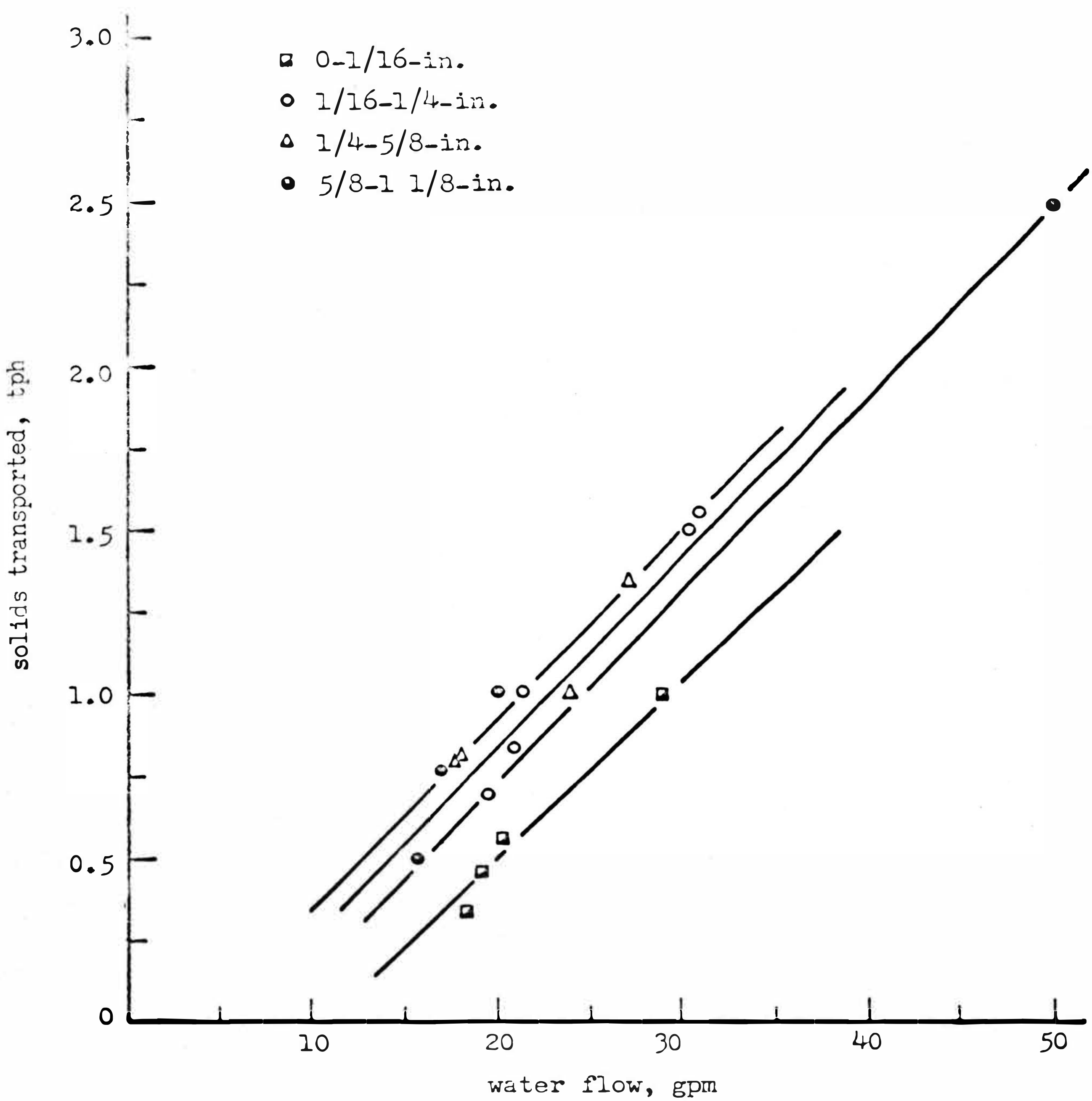

Figure 24. Effects of Particle Size upon

Slurry Flow

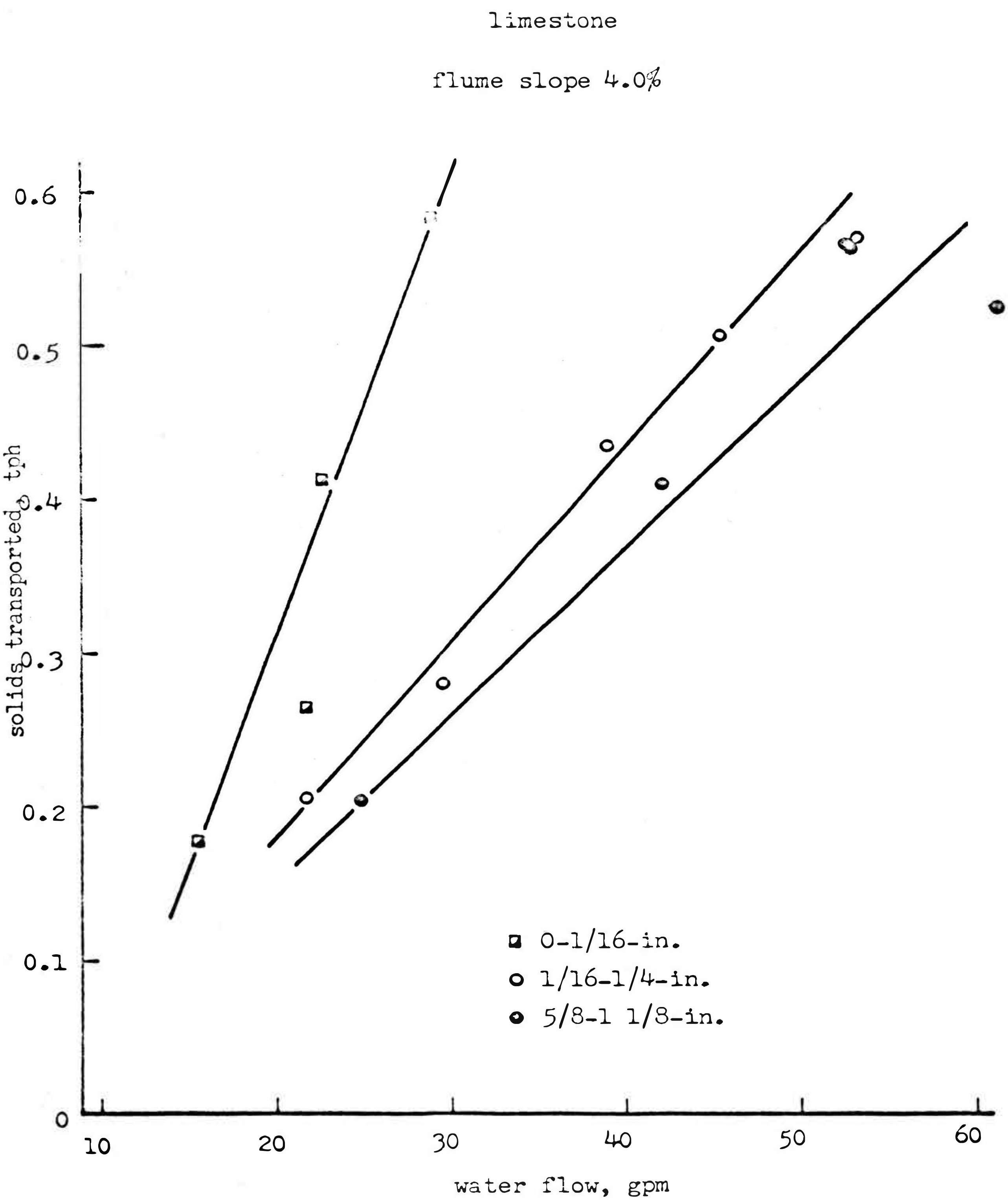

Figure 25. Effects of Particle Size upon Slurry Flow

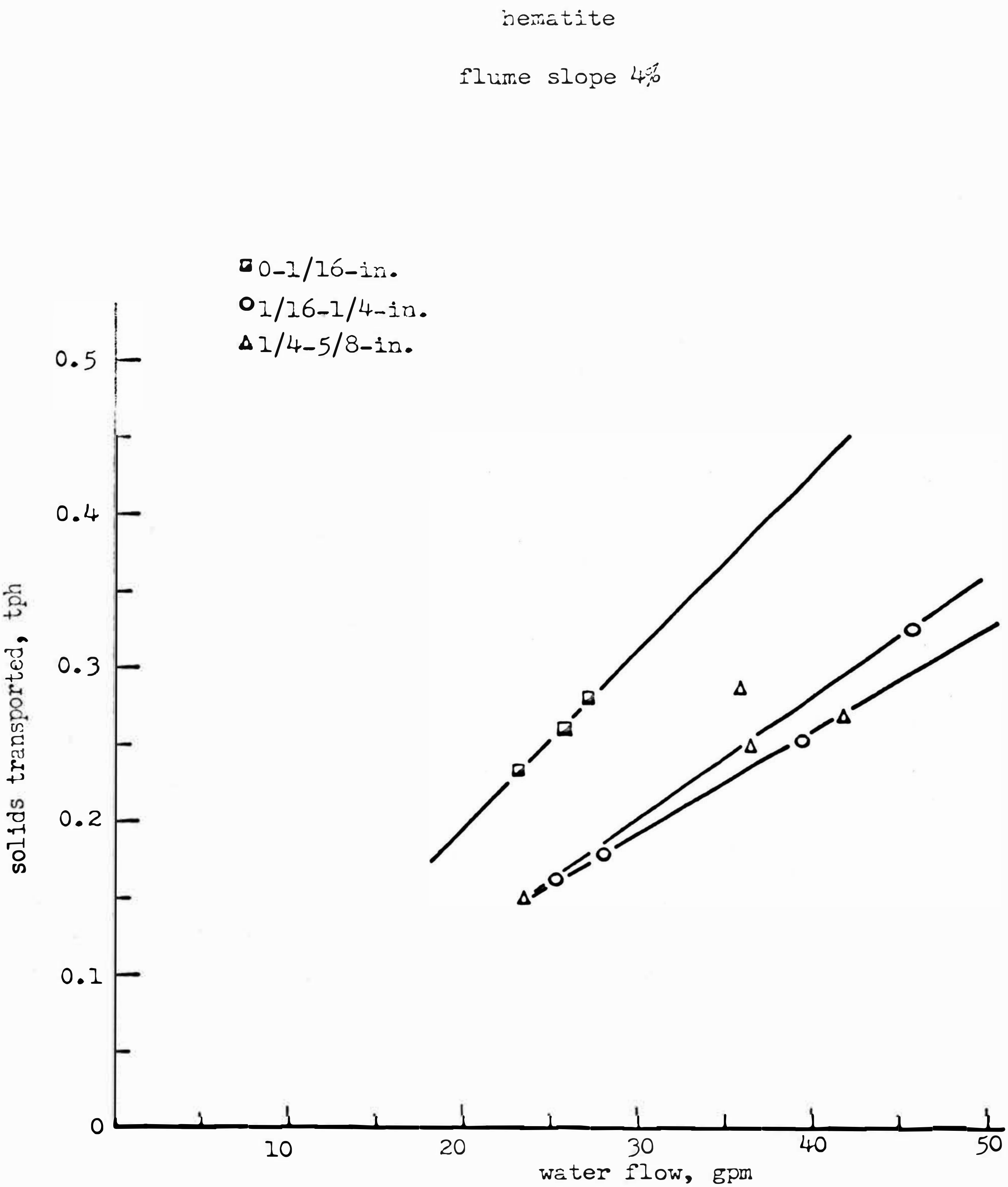

Figure 26. Effects of Particle Size

upon Slurry Flow

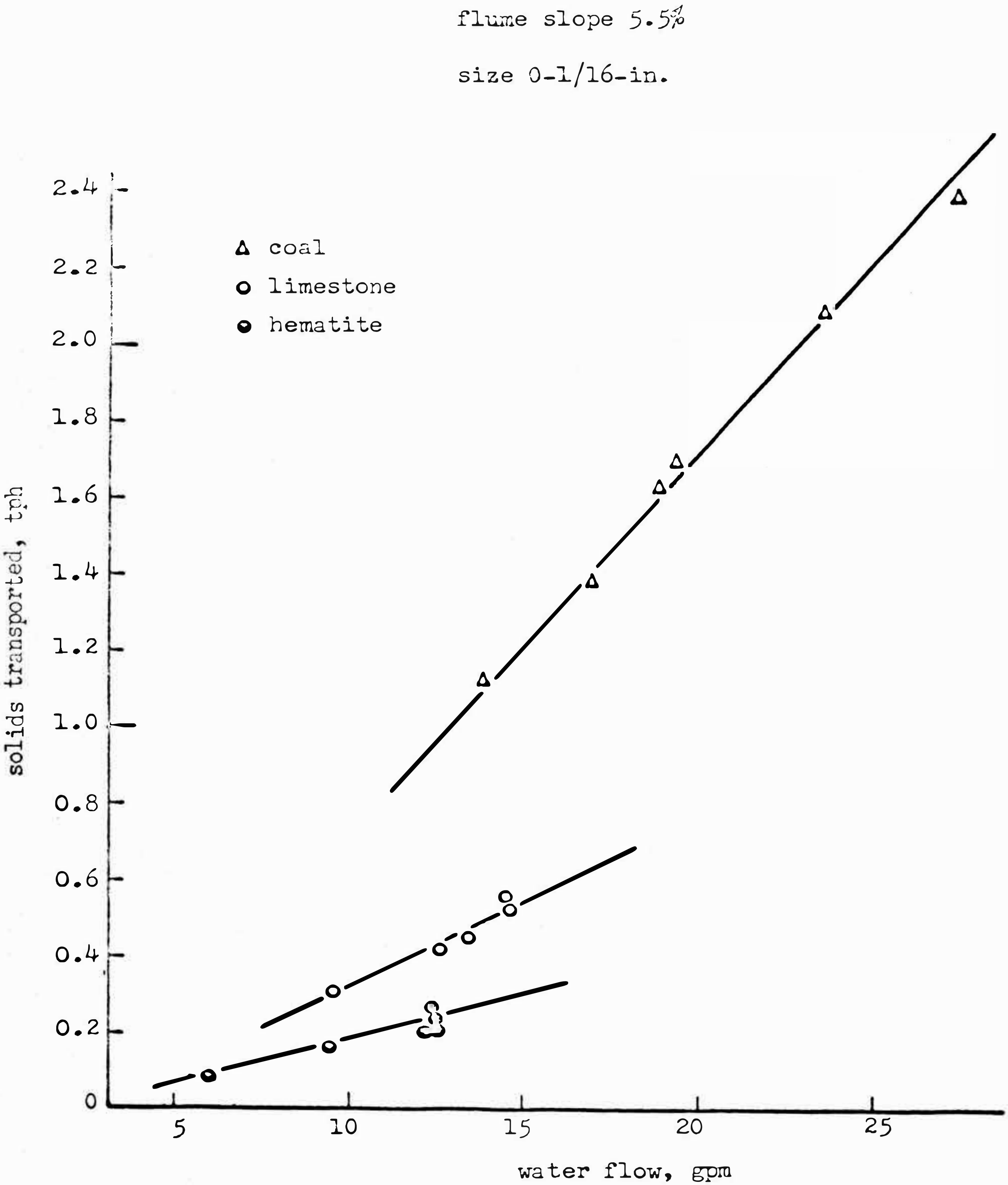

Figure 27. Effects of Particle Specific Gravity upon Slurry Flow

flume slope 5.5%

size 1/16-1/4-in.

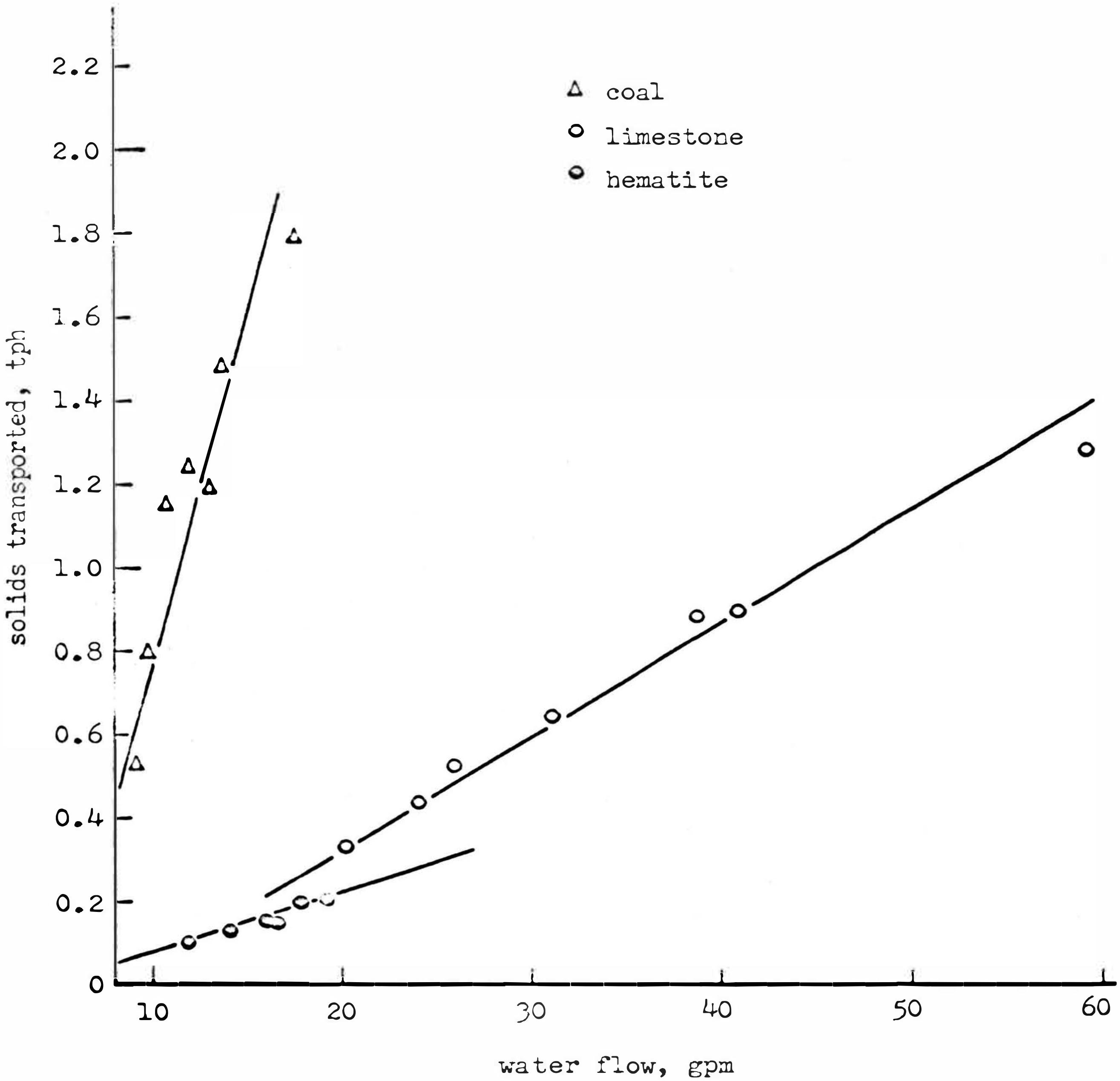

Figure 28. Effects of Particle Specific Gravity upon Slurry Flow

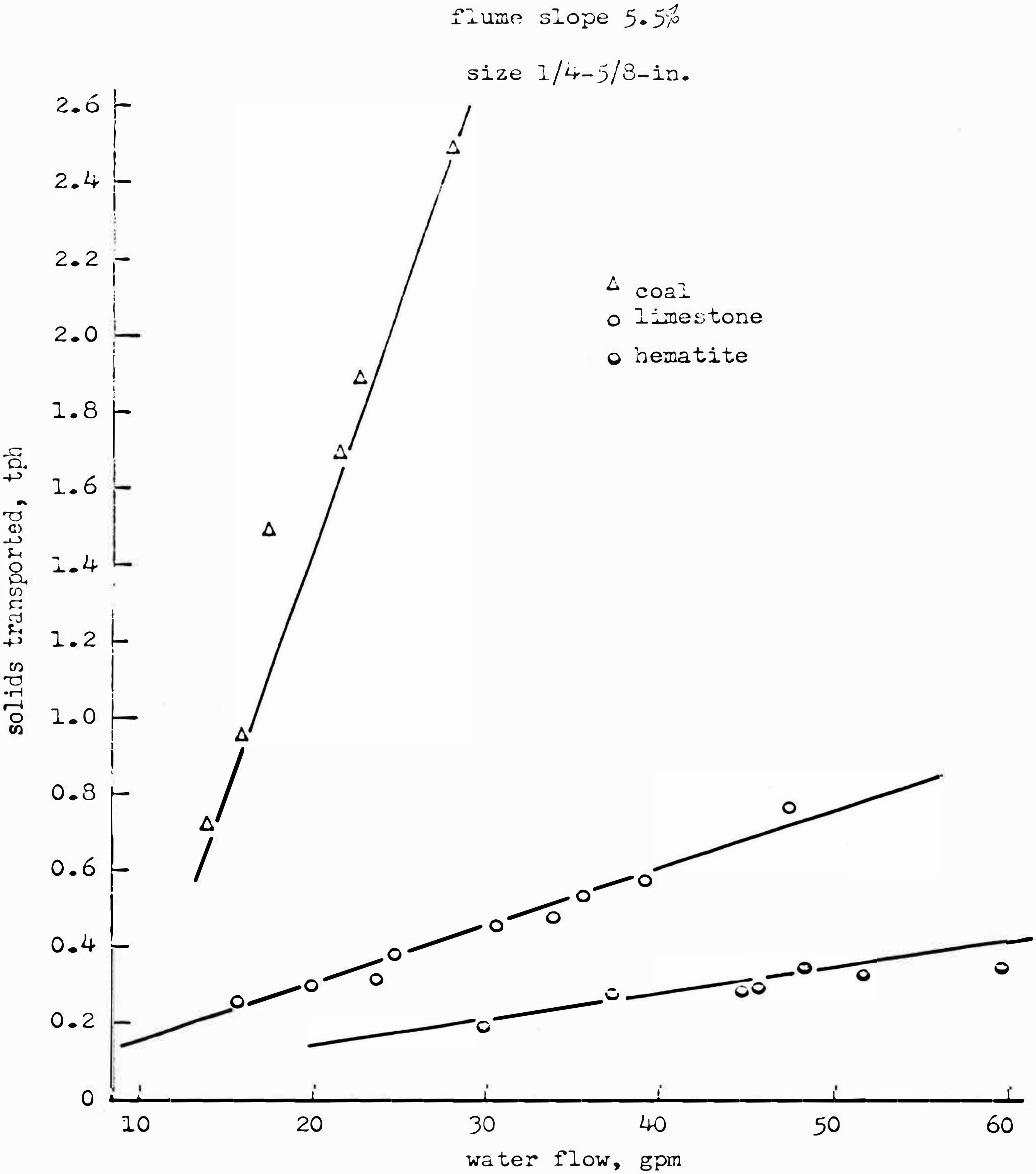

Figure 29. Effects of Particle Specific

Gravity upon Slurry Flow

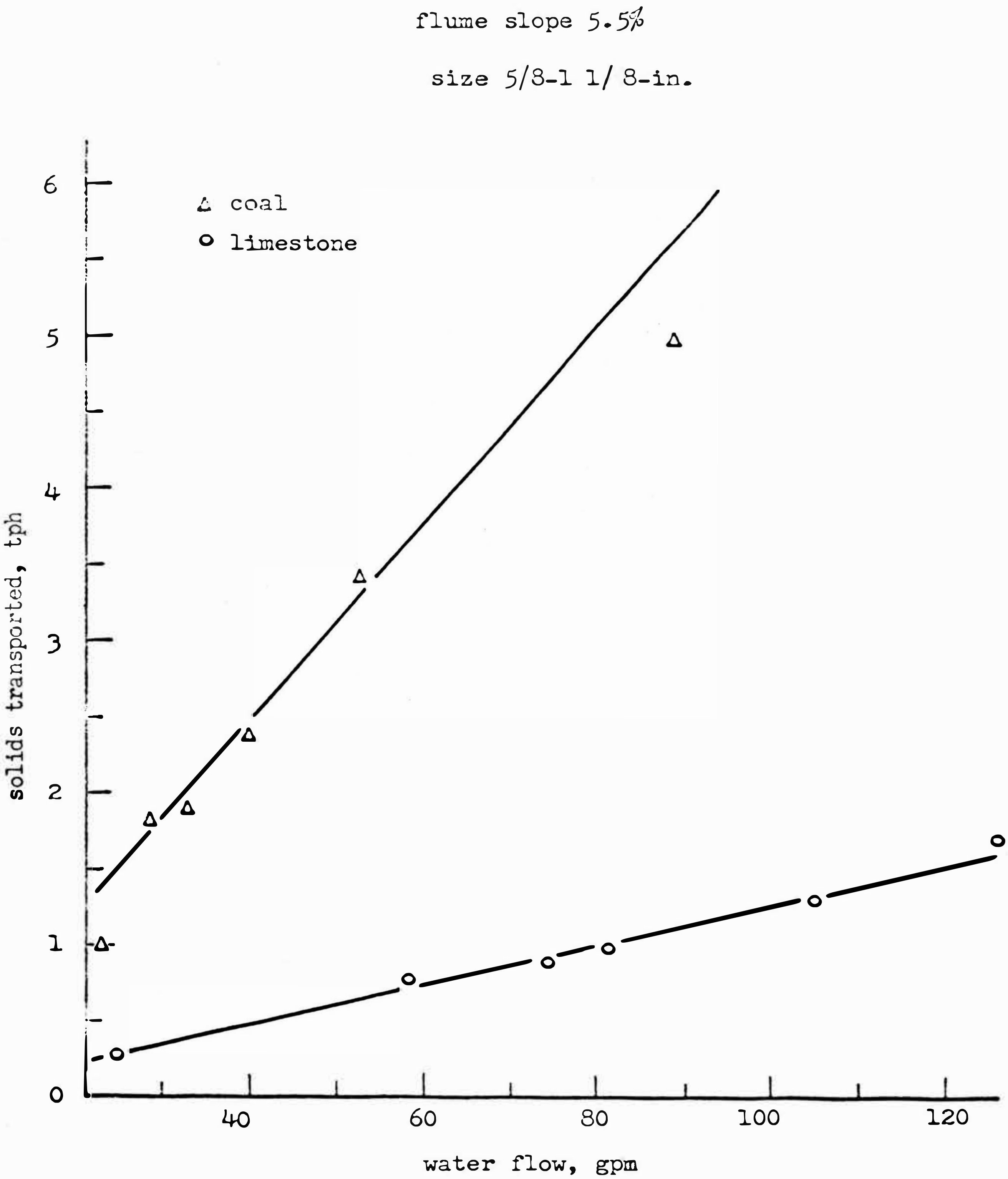

Figure 30. Effects of Particle Specific Gravity upon Slurry Flow

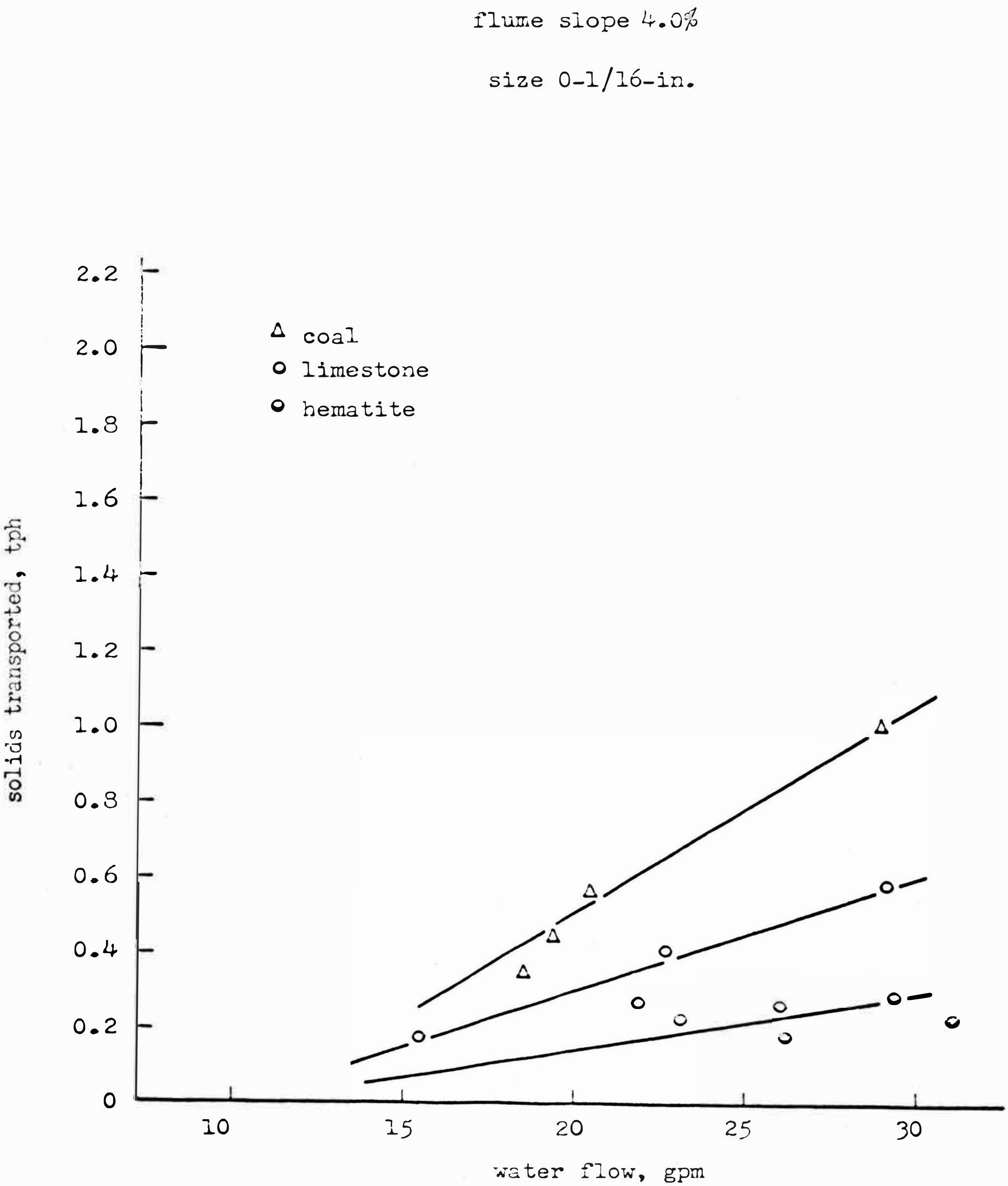

Figure 31. Effects of Particle Specific

Gravity upon Slurry Flow

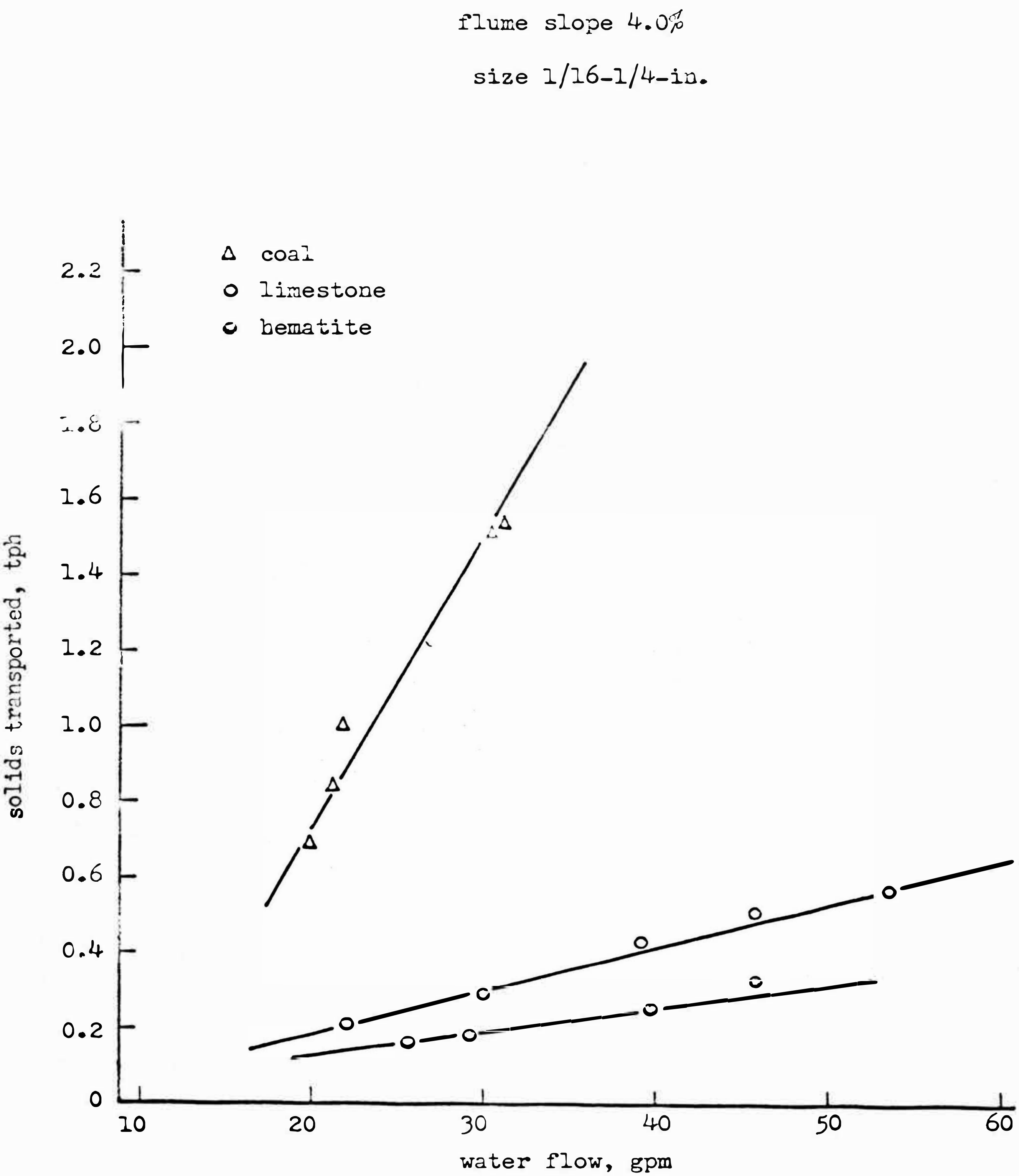

Figure 32. Effects of Particle Specific

Gravity upon Slurry Flow

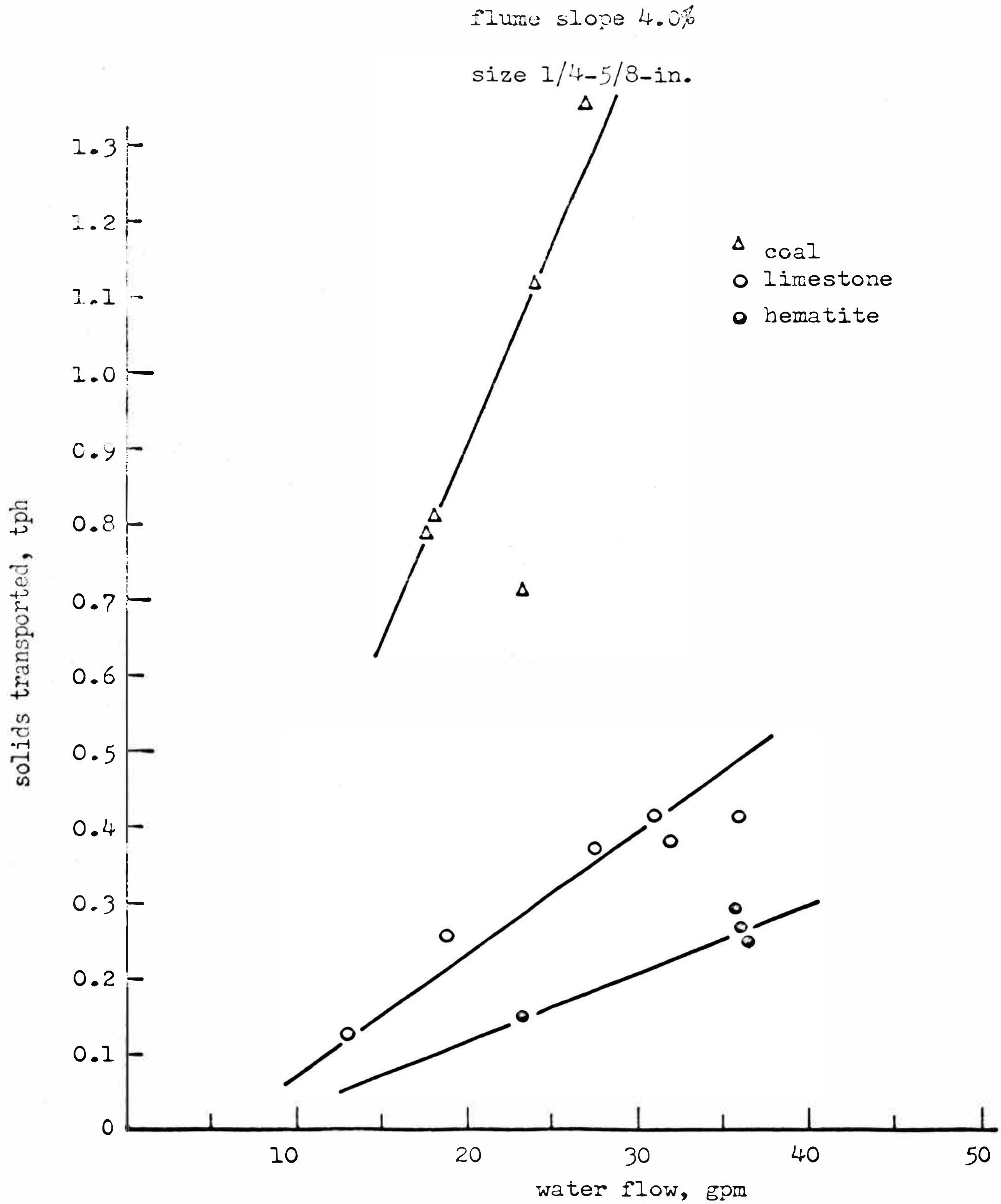

Figure 33. Effects of Particle Specific Gravity upon Slurry Flow

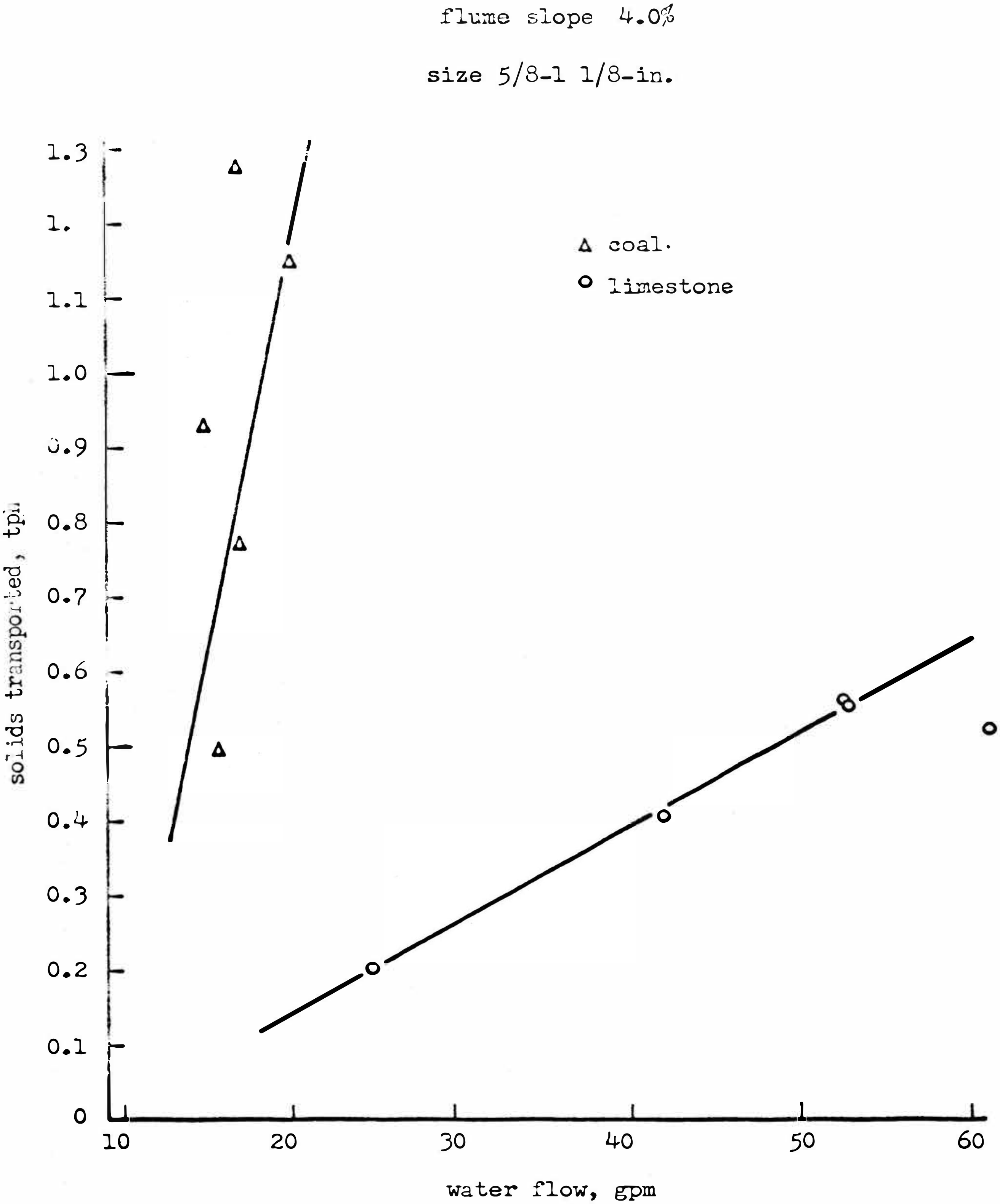

Figure 34. Effects of Particle Specific

Gravity upon Slurry Flow

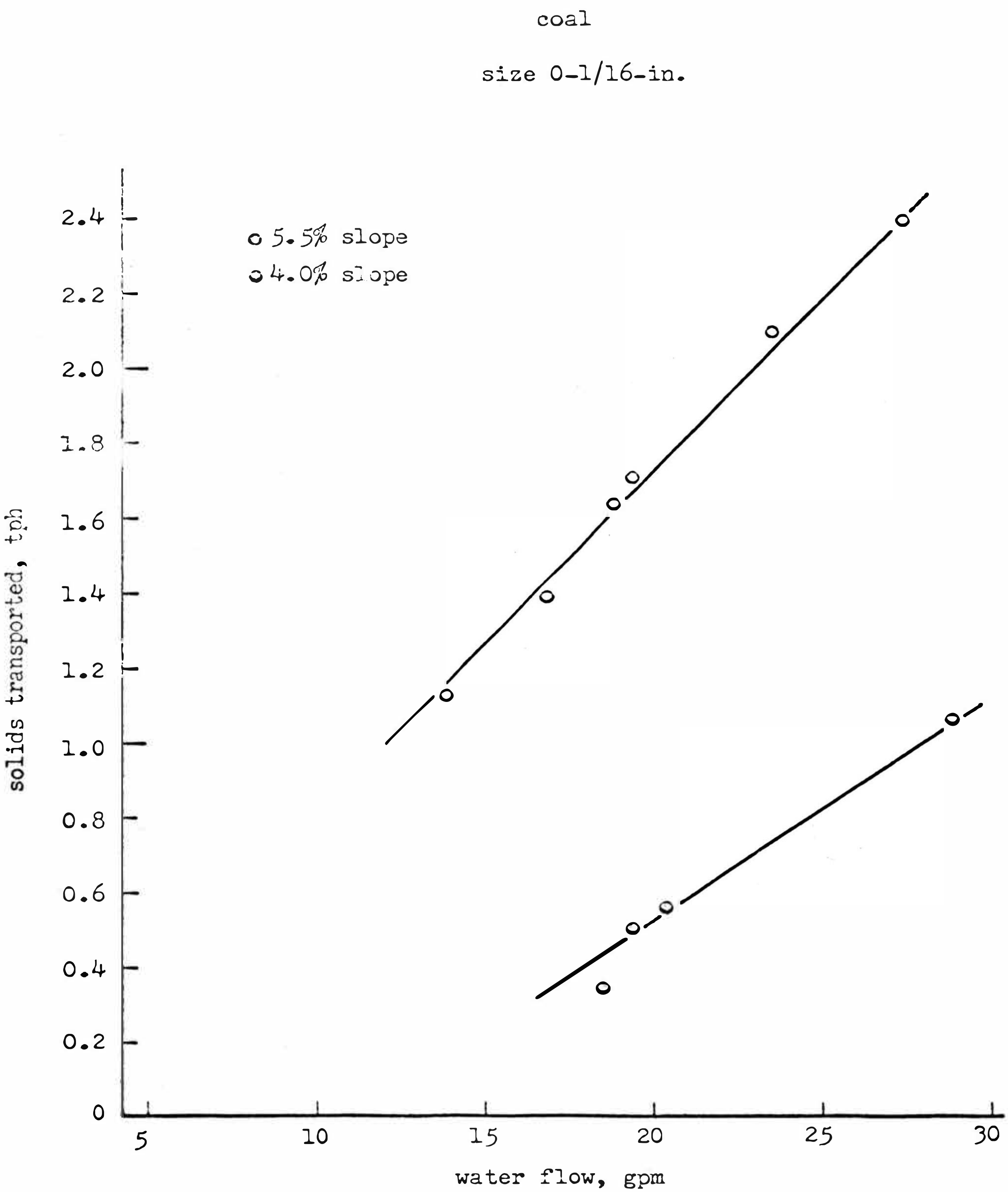

Figure 35. Effects of Flume Slope upon Slurry Flow

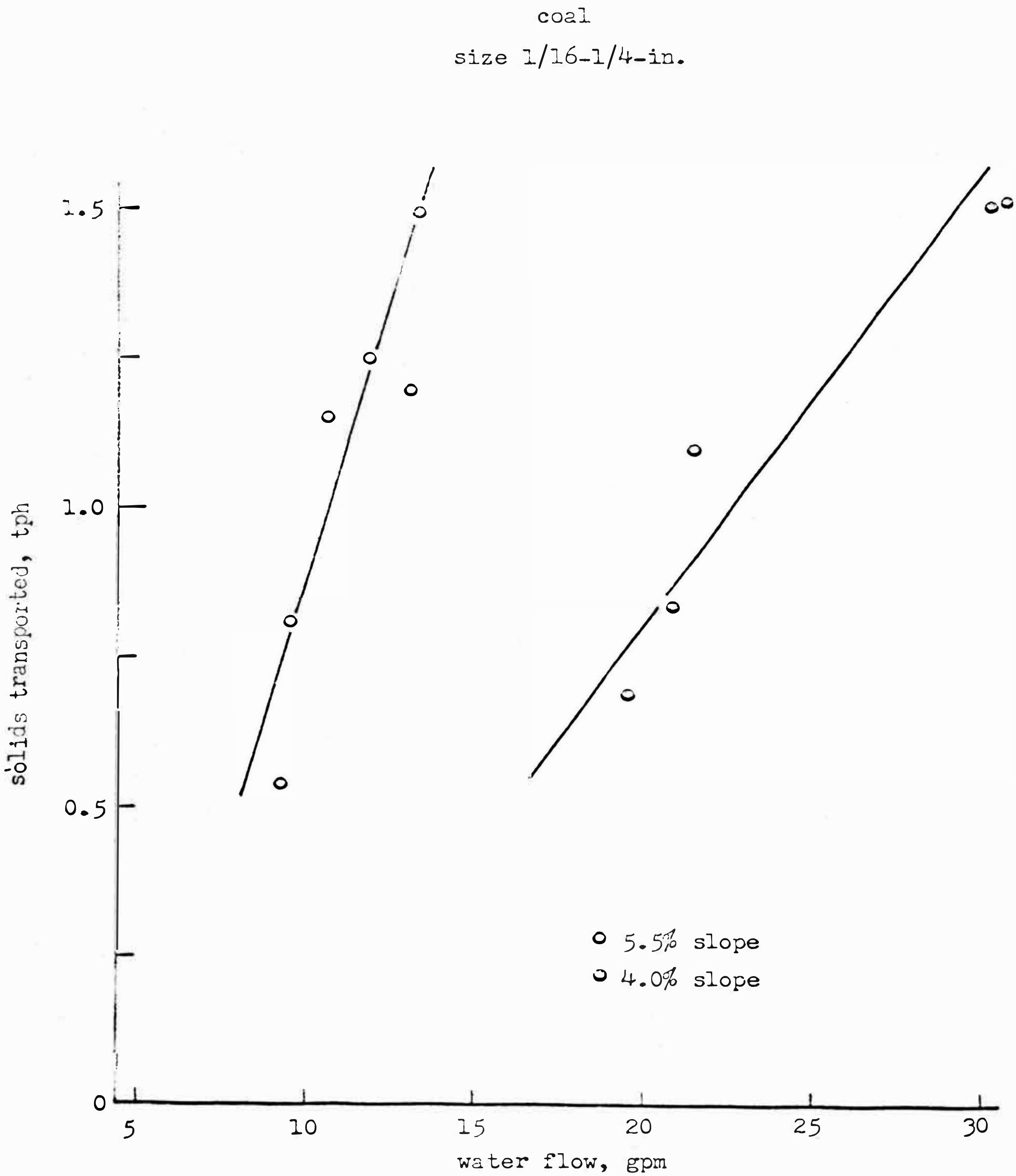

Figure 36. Effects of Flume Slope upon Slurry Flow

coal

size 1/4-5/8-in.

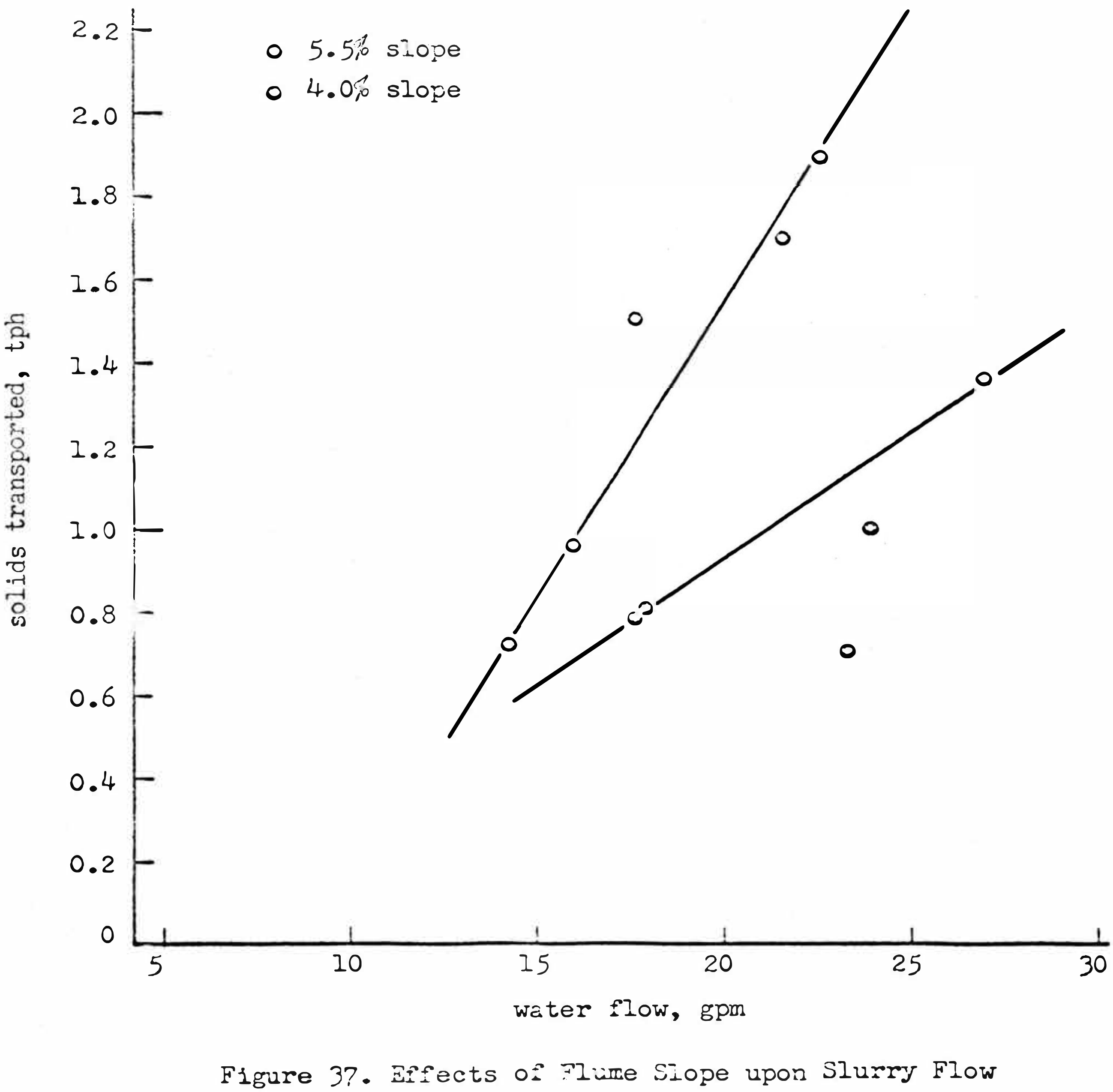

Figure 37. Effects of Flume Slope upon Slurry Flow

coal

size 5/8-1 1/8-in.

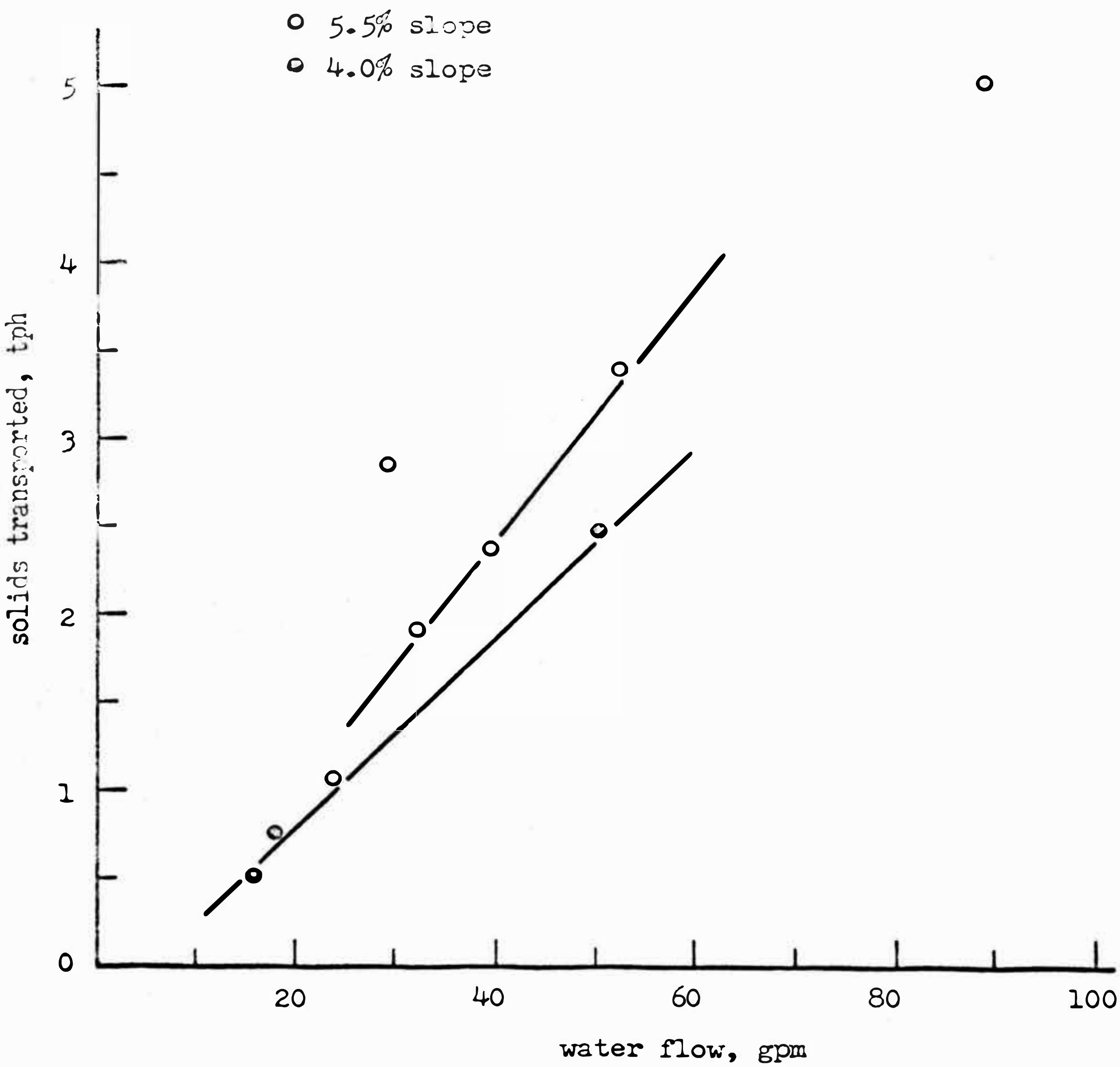

Figure 38. Effects of Flume Slope upon Slurry Flow

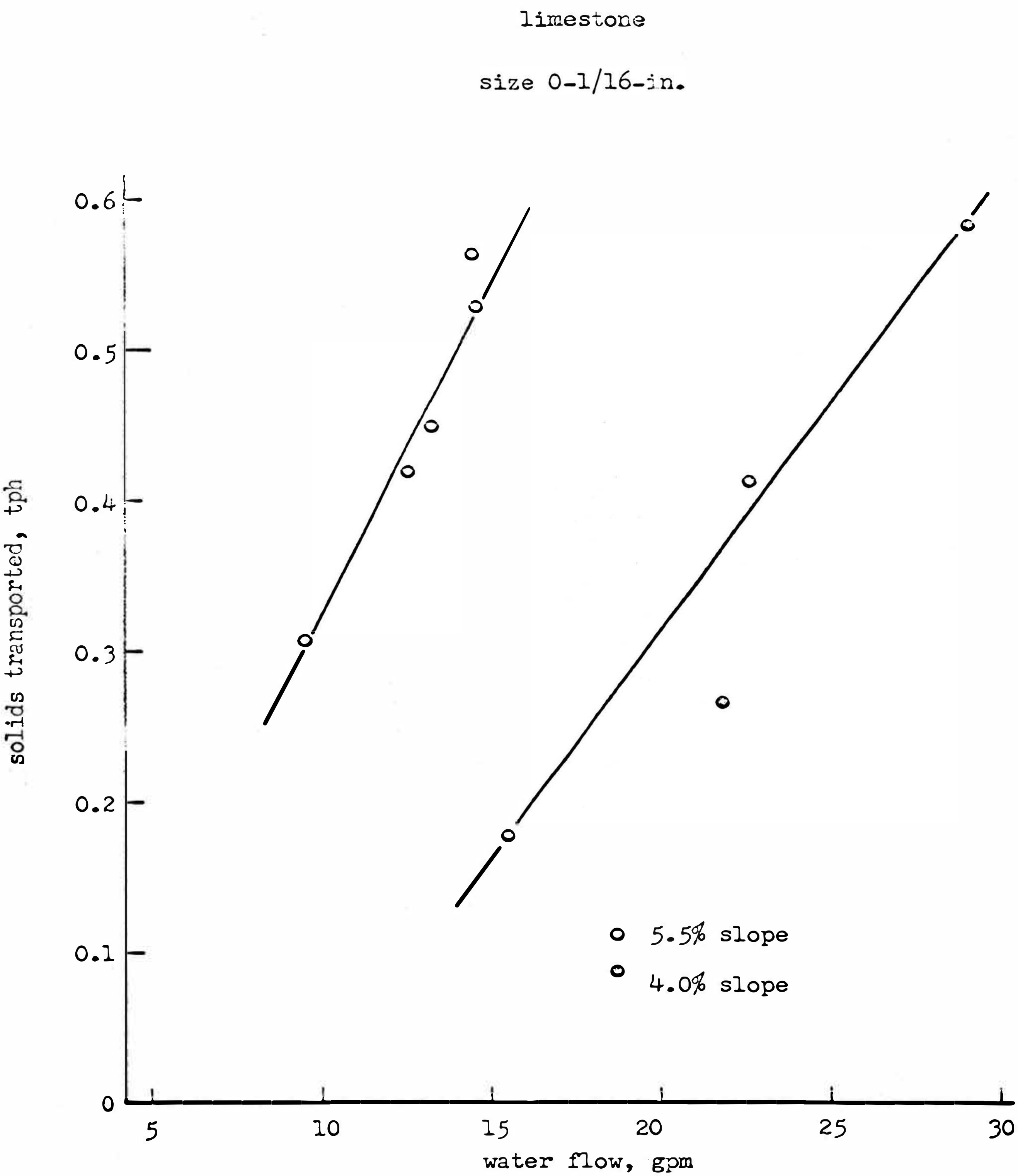

Figure 39. Effects of Flume Slope upon Slurry Flow

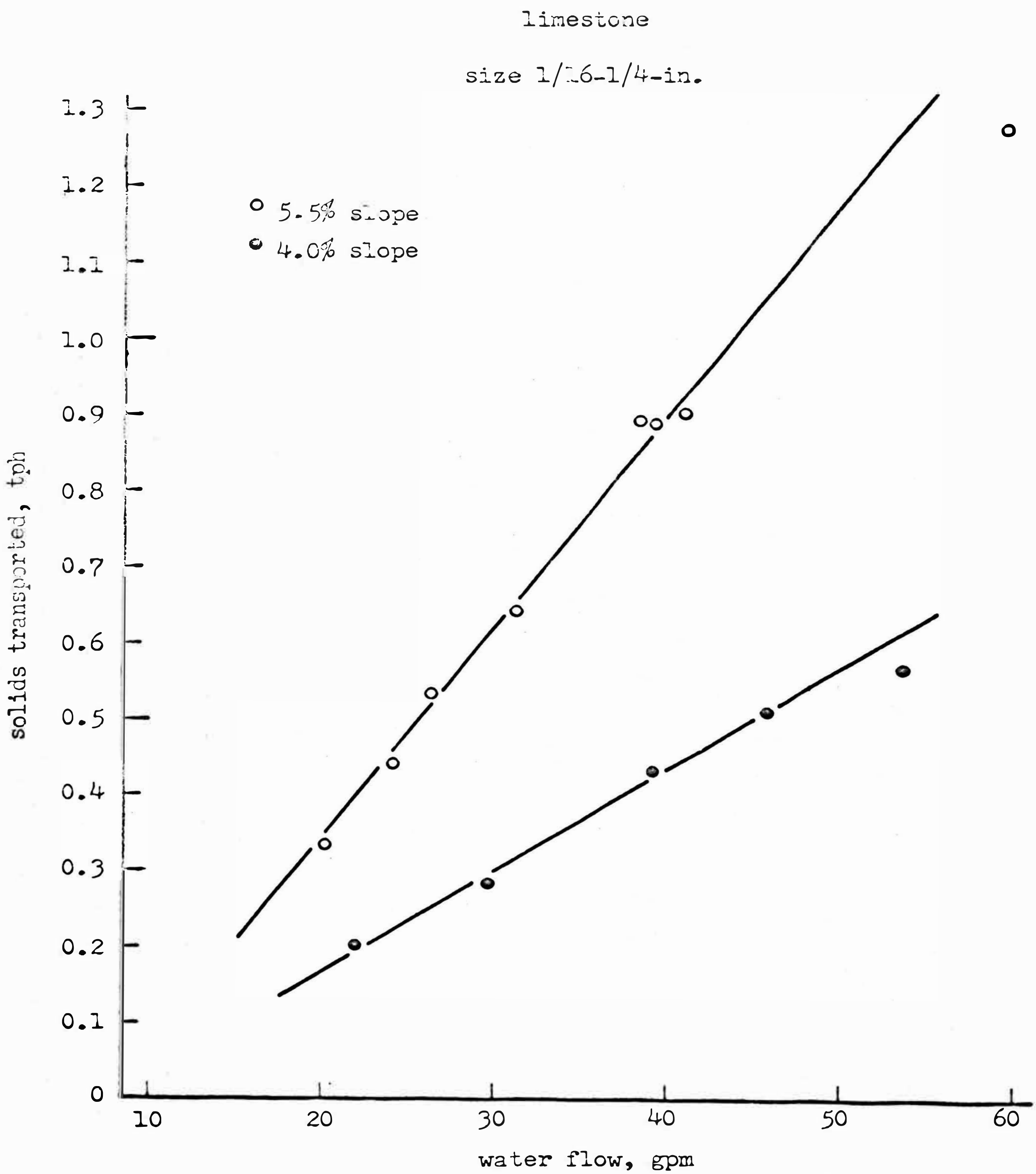

Figure 40 Effects of Flume Slope upon Slurry Flow

limestone

size 1/4-5/8-in.

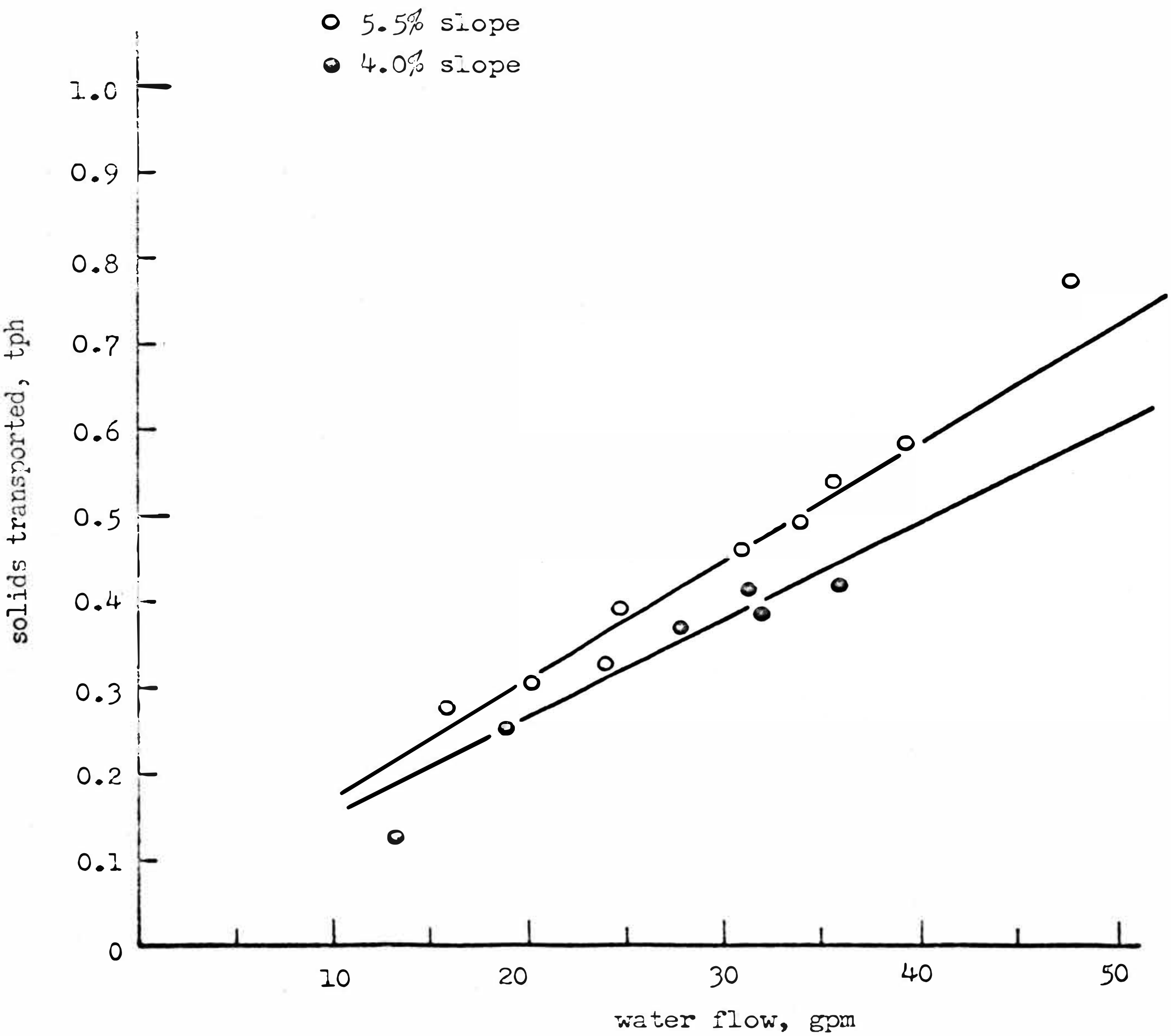

Figure 41. Effects of Flume Slope upon Slurry Flow

limestone

size 5/8-1 1/8-in.

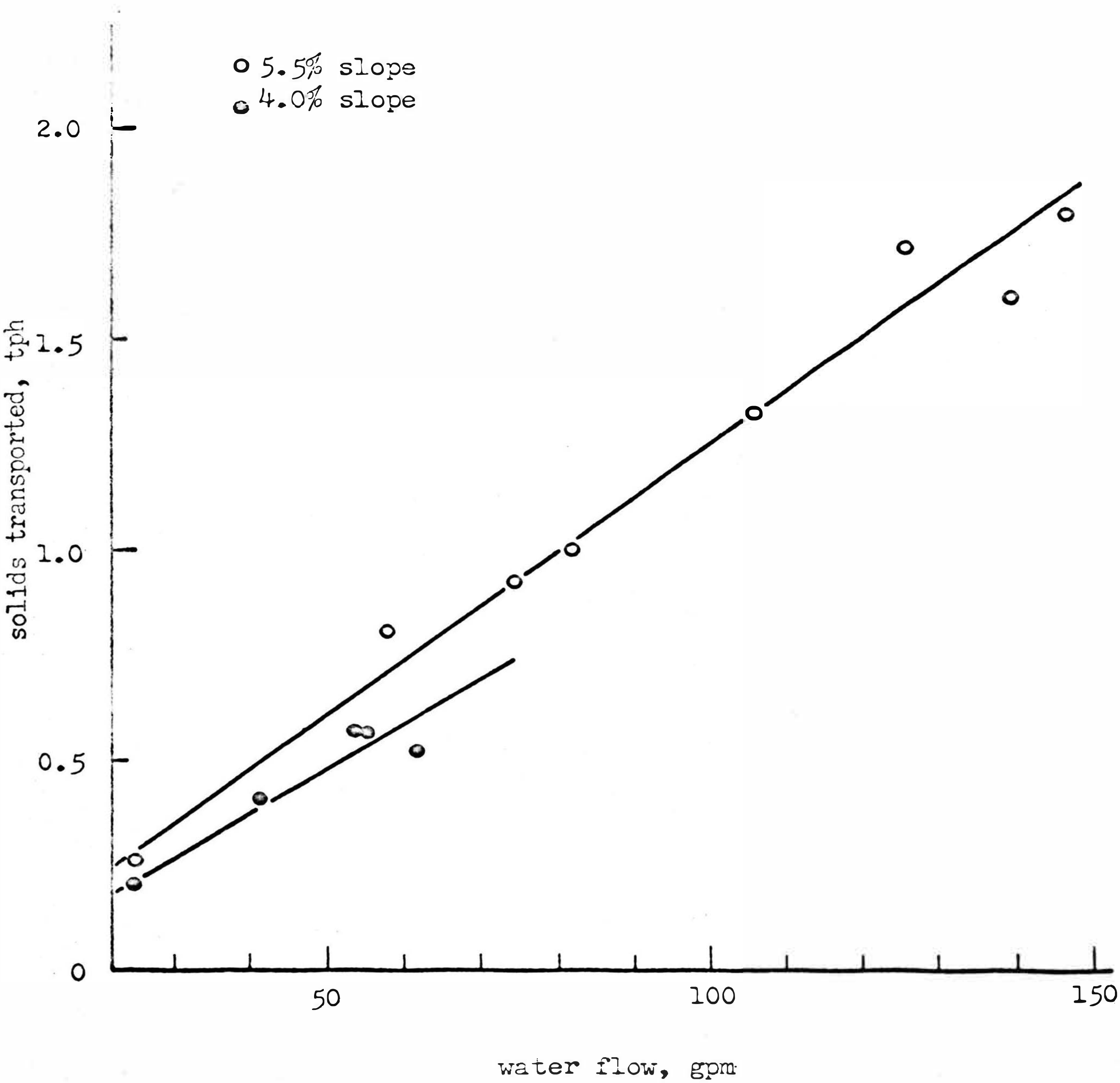

Figure 42. Effects of Flume Slope upon Slurry Flow

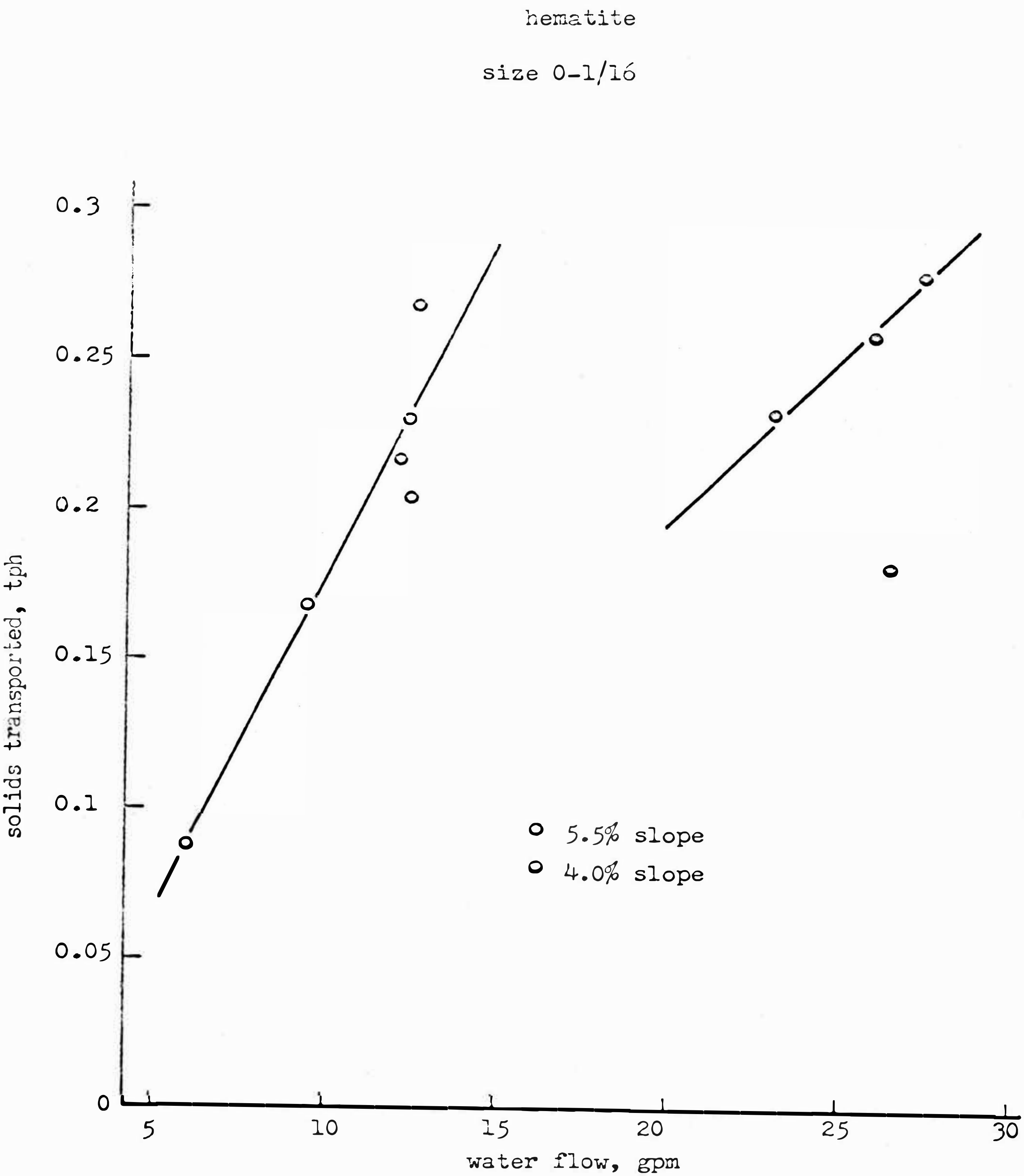

Figure 43. Effects of Flume Slope upon Slurry Flow

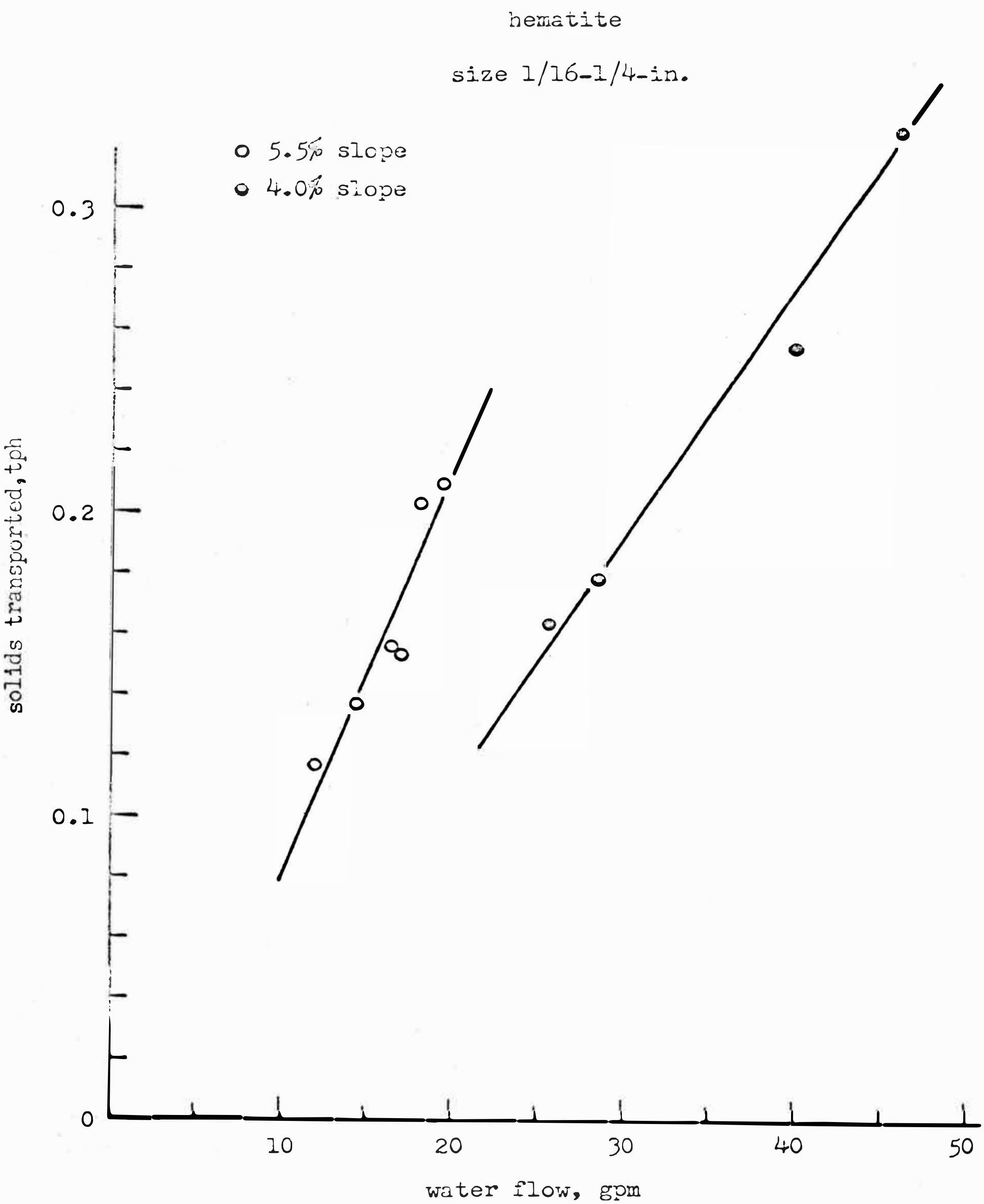

Figure 44. Effects of Flume Slope upon Slurry Flow

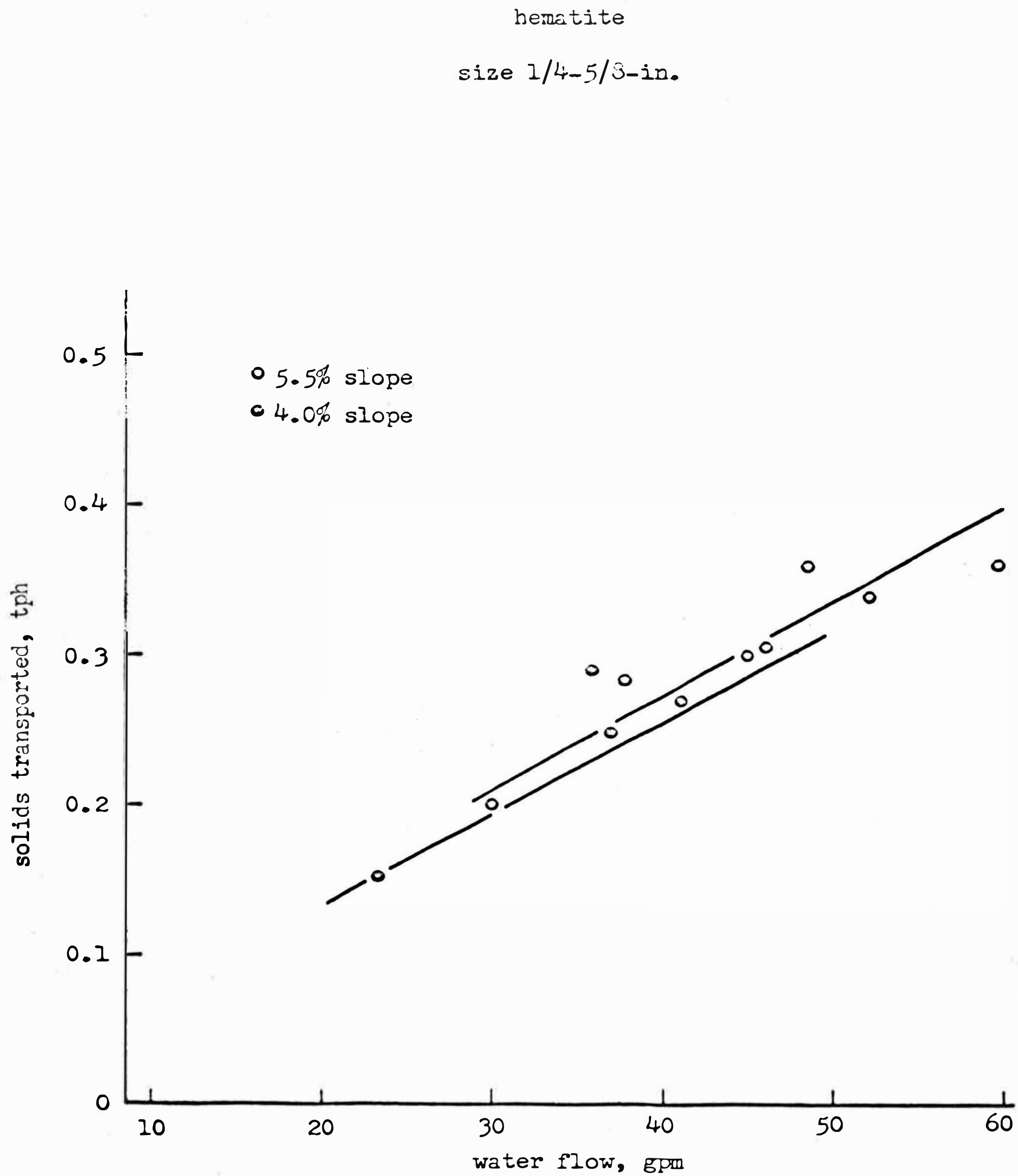

Figure 45. Effects of Flume Slope upon Slurry Flow

Observations

It was observed from the foregoing data that:

1. An increase in particle size decreases the solids-carrying capacity of water. However, this effect decreases as the flume slope decreases and the solids density increases.
2. An increase in particle specific gravity decreases the solids-carrying capacity of water. This effect decreases as the particle size increases and the flume slope decreases.
3. An increase in flume slope increases the solids-carrying capacity of water. The effect decreases as the particle size and the particle density increase.
4. An increase in the rate of water flow increases the solids-carrying capacity of water. This effect decreases with decreased flume slope and an increase in particle density.

All of the above parameters are obviously inter-related as summarized in Figure 46 and Tables 15 through 25, but their individual influences cannot be adequately identified, from the limited data available, to form a mathematical expression which

would apply to any general situation. Considerably more information must be obtained before such an attempt is warranted.

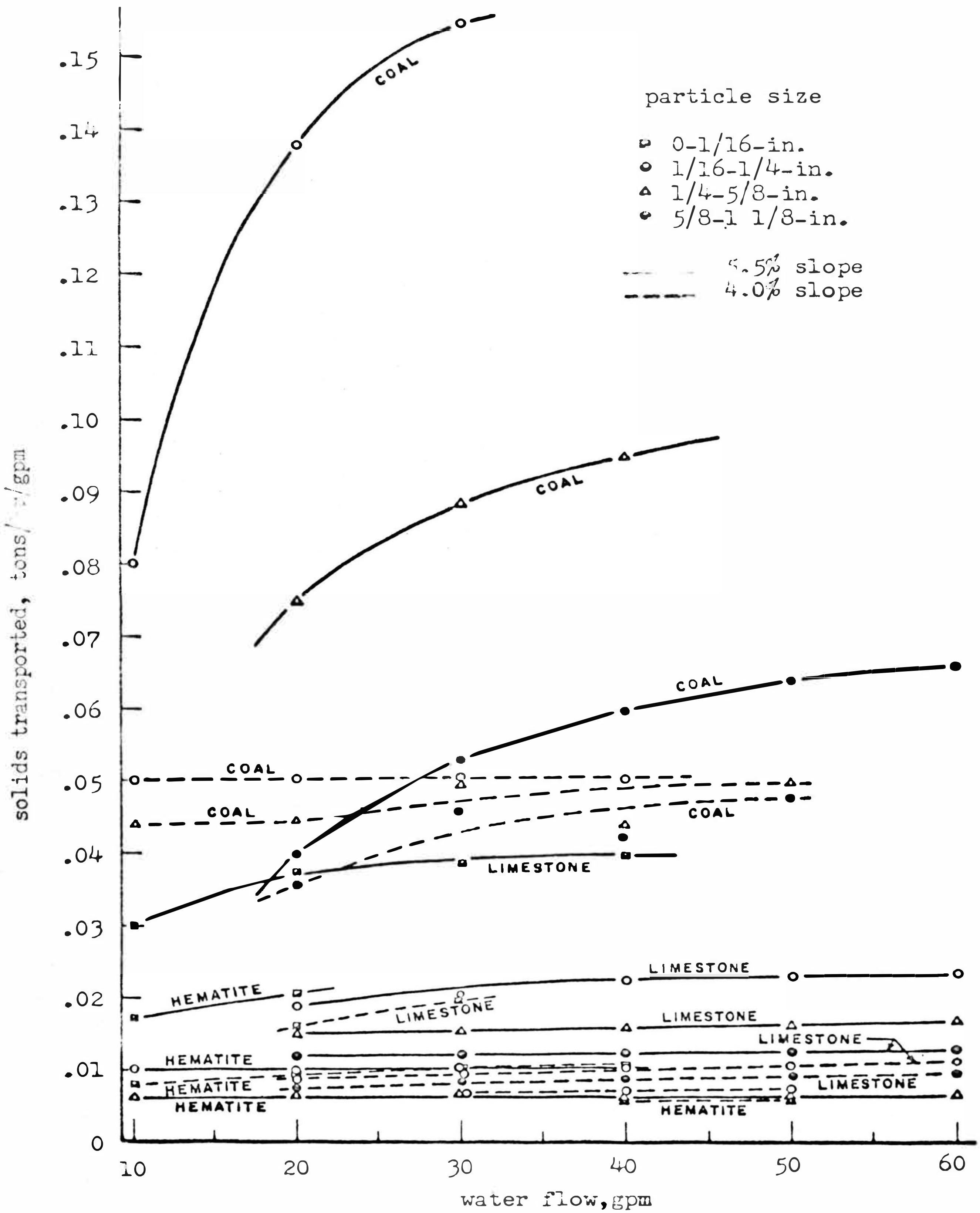

Figure 46. Flow Rate versus Carrying Capacity

(Tph/Gpm vs Gpm)

TABLE 15

Effect of Particle Size upon

Carrying Capacity

Particle size	Water Required, in gpm.					
	10	20	30	40	50	60
1/16-1/4-in.	(.08) 0.8	(.138) 2.75	(.155) 4.65	—	—	—
		1.8	1.75			
1/4-5/8-in.	—	(.075) 1.50	(.0883) 2.65	(.095) 3.80	—	—
			1.65	1.57		
5/8-1 1/8-in.	—	(.04) 0.80	(.053) 1.60	(.06) 2.40	(.064) 3.2	(.066) 4.0

Legend:
Tons per Hour of Coal on a 5.5 Percent Flume Slope

- - Ratio of Adjacent Values

( ) Tons/Hr/gpm

TABLE 16

Effect of Particle Size upon

Carrying Capacity

Particle size	Water Required, in gpm.					
	20	40	60	80	100	120
0-1/16-in.	(.0375) 0.75	(.04) 1.6	—	—	—	—
	1.9	1.78				
1/16-1/4-in.	(.019) 0.38	(.022) 0.9	(.024) 1.42	(.024) 1.95	—	—
	1.27	1.4	1.4	1.45		
1/4-5/8-in.	(.015) 0.30	(.016) 0.64	(.017) 1.00	(.017) 1.34	(.017) 1.70	—
	1.25	1.28	1.36	1.34	1.39	
5/8-1 1/8-in.	(.012) 0.24	(.012) 0.50	(.012) 0.74	(.0125) 1.00	(.0124) 1.24	(.0125) 1.50

Legend:
Tons per Hou
of Limestone
on a 5.5 Percent
Flume Slope

- - Ratio of
Adjacent Values

( ) Tons/Hr/gpm

TABLE 17

Effect of Particle Size upon

Carrying Capacity

	Water Required, in gpm.					
Particle size	10	20	30	40	50	60
0-1/16-in.	(.017) 0.17	(.0205) 0.41	–	–	–	–
	1.7	2.0				
1/16-1/4-in.	(.010) 0.10	(.010) 0.20	(.01) 0.30	(.0102) 0.41	–	–
	1.67	1.54	1.50	1.58		
1/4-5/8-in.	(.006) 0.06	(.006) 0.13	(.0066) 0.20	(.007) 0.26	(.007) 0.33	(.007) 0.40

Legend:
Tons per Hour of Hematite on a 5.5 Percent Flume Slope

- - Ratio of Adjacent Values

( ) Tons/Hr/gpm

TABLE 18

Effect of Particle Size upon

Carrying Capacity

Particle size	Water Required, in gpm. 10	20	30	40	50	60
	(.05)	(.05)	(.05)	(.05)		
1/16-1/4-in.	0.50	1.0	1.52	2.0	—	—
	1.1	1.12	1.0	1.14		
	(.044)	(.045)	(.05)	(.044)	(.05)	
1/4-5/8-in.	0.44	0.89	1.50	1.76	2.5	—
		1.2	1.07	1.04	1.04	
		(.036)	(.046)	(.043)	(.048)	
5/8-1 1/8-in.		0.72	1.40	1.70	2.4	—

Legend:
Tons per Hour
of Coal on a
4.0 Percent
Flume Slope

- - Ratio of
Adjacent Values

( ) Tons/Hr/gpm

TABLE 19

Effect of Particle Size upon

Carrying Capacity

Particle size	Water Required, in gpm					
	10	20	30	40	50	60
0-1/16-in.		(.015) 0.3	(.02) 0.6	–	–	–
		1.66	2.0			
1/16-1/4-in.		(.009) 0.18	(.01) 0.3	(.01) .43	(.011) .56	(.011) .68
		1.1	1.07	1.1	1.08	
1/4-5/8-in.		(.008) 0.16	(.009) 0.28	(.0097) 0.39	(.010) .52	–
		1.07	1.08	1.08	1.1	
5/8-1 1/8-in.		(.0075) 0.15	(.0086) 0.26	(.009) 0.36	(.0094) .47	(.0096) .58

Legend:
Tons per Hour of Limestone on a 4.0 Percent Flume Slope

- - Ratio of Adjacent Values

( ) Tons/Hr/gpm

TABLE 20

Effect of Particle Size upon

Carrying Capacity

Particle size	Water Required, in gpm.					
	10	20	30	40	50	60
0-1/16-in.	(.008) .08	(.0095) .19	(.0103) .31	(.0107) .43	—	—
			1.55	1.54		
1/16-1/4-in.	—	—	(.007) .20	(.007) .28	(.0072) .36	—
				1.12	1.12	
1/4-5/8-in.	—	—	—	(.0063) .25	(.0064) .32	—

Legend:
Tons per Hour of Hematite on a 4.0 Percent Flume Slope

- - Ratio of Adjacent Values

( ) Tons/Hr/gpm

Effect of Size:

As portrayed in Figure 46 and Tables 15 through 20, the size of the particles partially determines the amount of water required for transportation of a given amount of material. As the size of the particles is increased, the water requirement for transporting the given amount of solids also increases.

Coal:

For transporting 0.8 tph of coal of 1/16-1/4-inch size requires only 10 gpm of water, whereas, twice this amount of water is necessary to move the same quantity of the 5/8-1 1/8-in. size material.

The ratio of the solids-carrying capacity of the water (the proportion of solids transportation capacity with varying particle parameters) decreases as the particle size increases. For example, the (carrying-capacity) ratio of 1/16-1/4-in. to 1/4-5/8-in. size coal is 1.75, while that of 1/4-5/8-in. to 5/8-1 1/8-in. only 1.65 at the same rate of 30 gpm of water.

Furthermore, when the flow rate is increased, the carrying capacity of water (tph/gpm) is also increased considerably (Figure 46).

Limestone:

From Table 16, it can be observed that the transportation ratio for particles between 0-1/16-in. and 1/16-1/4-in. is 1.78

at 40 gpm of water, between 1/16-1/4-in. and 1/4-5/8-in. it is 1.40, and between 1/4-5/8-in. and 5/8-1 1/8-in. it is 1.28. This indicates that the ratio decreases as the particle size increases. However, from the same table, it can be seen that, as before, the carrying capacity per gallon of water is increased as the flow rate is increased.

Hematite:

Hematite behaves in the same manner as coal and limestone as shown in Table 17. The transportation ratio of 0-1/16-in. to 1/16-1/4-in. size hematite is 2.0 at 20 gpm of water and is reduced to 1.54 as the sizes are increased from 1/16-1/4-in. to 1/4-5/8-in. The carrying capacity (tph/gpm) also increases as the flow rate is increased.

From the above three examples, it will be noted that when the size of coal is decreased to 1/16-1/4-in. from 5/8-1 1/8-in. the haulage capacity is increased by 100 percent, with the same quantity of water. Also, when the size of limestone is changed to 0-1/16-in. from 5/8-1 1/8-in. the production rate is increased to three times the original value. The results for hematite are the same when its size is reduced from 1/4-5/8-in. to 0-1/16-in. Similar effects were noted with a 4.0 percent flume slope.

Effect of Specific Gravity:

The specific gravity of the material is also an important factor in transporting solids in open flumes. Its affect upon

TABLE 21

Effect of Specific Gravity on

Carrying Capacity

Material	Sp.Gr.	Water Required, in gpm.						
		10	20	30	40	50	60	70
Coal	1.27	–	–	–	–	–	–	–
Limestone	2.67	0.3 (.0375)	.75 (.038)	1.16 (.0386)	1.6 (.04)	–	–	–
(Ratio)		1.76	1.83					
Hematite	4.04	0.17 (.017)	.41 (.0205)	–	–	–	–	–
Coal	1.27	0.8 (.08)	2.75 (.138)	4.65 (.155)	–	–	–	–
(Ratio)			7.2	7.5				
Limestone	2.67	–	0.38	.62	.9 (.022)	1.16 (.0232)	1.42 (.024)	–
(Ratio)			1.9	2.06	2.2			
Hematite	4.04	.10 (.010)	.20 (.010)	.30 (.010)	.41 (.010)	–	–	–

Legend:

Tons per Hour of Solids 0-1/16-in. size on a 5.5 Percent Flume Slope
- - Ratios of Adjacent Values
( ) Tons/Hr/gpm

Tons per Hour of Solids 1/16-1/4-in. size on a 5.5 Percent Flume Slope
- - Ratios of Adjacent Values
( ) Tons/Hr/gpm

TABLE 21 (Continued)

Material	Sp.Gr.	10	20	30	40	50	60	70	
			(.075)	(.0883)	(.095)				Tons per Hour of Solids 1/4-5/8-in. size on a 5.5 Percent Flume Slope
Coal	1.27	–	1.5	2.65	3.8	–	–	–	
			5.0	5.75	5.9				
Limestone	2.67	–	0.3	0.46	0.64	0.8	1.0	1.18	
			2.3	2.3	2.45	2.4	2.5		- - Ratios of Adjacent Values
Hematite	4.04	.06	0.13	0.20	0.26	0.33	0.40	–	
		(.006)	(.006)	(.0066)	(.007)	(.007)	(.007)		( ) Tons/Hr/gpm
			(.04)	(.053)	(.06)	(.064)	(.066)		
Coal	1.27	–	0.8	1.6	2.4	3.2	4.0	–	Tons per Hour of Solids 5/8-1 1/8-in. size on a 5.5 Percent Flume Slope
			3.34	4.4	4.8	5.3	5.4		- - Ratios of Adjacent of
Limestone	2.67	–	.24	.36	.50	.62	.74	–	
			(.012)	(.012)	(.012)	(.0124)	(.012)		( ) Tons/Hr/gpm
Hematite	4.04	–	–	–	–	–	–	–	

TABLE 22

Effect of Specific Gravity on

Carrying Capacity

Material	Sp.Gr.	10		20		30		40		50		60		70
		Water Required, in gpm.												
Coal	1.27	—		—		—		—		—		—		—
Limestone	2.67	—		(.015) 0.3	2.0	(.02) 0.6		—		—		—		—
Hematite	4.04	(.008) .08	2.38	(.0095) .19	1.63	(.0103) .31	1.38	(.0107) .43		—		—		—
Coal	1.27	(.05) 0.5	2.0	(.05) 1.00	1.52	(.05) 1.52	1.3	(.05) 2.0		—		—		—
Limestone	2.67	—		(.009) 0.18	1.67	(.01) 0.3	1.43	(.010) 0.43	1.3	(.011) 0.56	1.21	(.011) 0.68		—
Hematite	4.04	—		—		(.007) 0.20	1.4	(.007) 0.28	1.28	(.0072) 0.36		—		—

Legend (first three rows):
Tons per Hour of Solids 0-1/16-in. size on a 4.0 Percent Flume Slope
- - Ratios of Adjacent Values
( ) Tons/Hr/gpm

Legend (last three rows):
Tons per Hour of Solids 1/16-1/4-in. size on a 4.0 Percent Flume Slope
- - Ratios of Adjacent Values
( ) Tons/Hr/gpm

TABLE 22 (Continued)

Material Sp.Gr.		10	20	30	40	50	60	70	
Coal	1.27	(.044) 0.44 - 2.3 -	(.045) 0.89 - 1.69 -	(.05) 1.50 - 1.17 -	(.044) 1.76 - 1.42 -	(.05) 2.5	—	—	Tons per Hour of Solids 1/4-5/8-in. size on a 4.0 Percent Flume Slope - - Ratios of Adjacent Values ( ) Tons/Hr/gpm
Limestone	2.67	—	(.008) 0.16 - 1.75 -	(.009) 0.28 - 1.39 -	(.0097) 0.39 - 1.34 -	(.010) 0.52	—	—	
Hematite	4.04	—	—	—	(.0063) 0.25 - 1.28 -	(.0064) 0.32	—	—	
Coal	1.27	(.038) 0.38 - 1.9 -	(.036) 0.72 - 1.95 -	(.046) 1.40 - 1.21 -	(.043) 1.70 - 1.4 -	(.048) 2.40	—	—	Tons per Hour of Solids 5/8-1 1/8-in. size on a 4.0 Percent Flume Slope - - Ratios of Adjacent Values ( ) Tons/Hr/gpm
Limestone	2.67	—	(.0075) 0.15 - 1.73 -	(.0086) 0.26 - 1.38 -	(.009) 0.36 - 1.30 -	(.0094) 0.47 - 1.23 -	(.0096) 0.58	—	
Hematite	4.04	—	—	—	—	—	—	—	

TABLE 23

Effect of Slope upon

Carrying Capacity

	Water Required, in. gpm.						
Slope Percent	10	20	30	40	50	60	Legend:
	(.08)	(.138)	(.155)				Tons per Hour of Coal 1/16-1/4-in. size
5.5	0.8	2.75	4.65	6.5	—	—	- - Ratios of Adjacent Values
	1.6	2.7	3.5	3.2			( ) Tons/Hr/gpm
4.0	0.5	1.00	1.52	2.0	—	—	
	(.05)	(.05)	(.05)	(.05)			
		(.075)	(.0883)	(.095)			Tons per Hour of Coal 1/4-5/8-in. size
5.5	—	1.5	2.65	3.8	—	—	- - Ratios of Adjacent Values
		1.69	1.76	2.15			( ) Tons/Hr/gpm
4.0	.44	.89	1.50	1.76	2.5	—	
	(.044)	(.045)	(.05)	(.044)	(.05)		
		(.04)	(.053)	(.06)	(.064)	(.066)	Tons per Hour of Coal 5/8-1 1/8-in. size
5.5	—	0.8	1.60	2.40	3.2	4.0	- - Ratios of Adjacent Values
		1.1	1.1	1.4	1.3		( ) Tons/Hr/gpm
4.0	—	0.72	1.40	1.70	2.4	—	
		(.036)	(.046)	(.043)	(.048)		

TABLE 24

Effect of Slope upon

Carrying Capacity

Water Required, in gpm.								
Slope Percent	10	20	30	40	50	60	70	
	(.03)	(.0375)	(.0386)	(.04)				Legend: Tons per Hour of Limestone 0-1/16-in. size
5.5	0.3	0.75	1.16	1.6	—	—	—	
		2.5	1.9					- - Ratios of Adjacent Values
4.0	—	0.30	0.6	—	—	—	—	( ) Tons/Hr/gpm
		(.015)	(.02)					
		(.019)	(.0206)	(.022)	(.0232)	(.024)		Tons per Hour of Limestone 1/16-1/4-in. size
5.5	0.16	0.38	0.62	0.9	1.16	1.42	1.7	
		2.1	2.0	2.1	2.15	2.1		- - Ratios of Adjacent Values
4.0	—	0.18	0.30	0.43	0.56	0.68	—	( ) Tons/Hr/gpm
		(.009)	(.01)	(.010)	(.011)	(.011)		
		(.015)	(.0153)	(.016)	(.016)	(.017)		
5.5	—	0.30	0.46	0.64	0.82	1.0	1.18	Tons per Hour of Limestone 1/4-5/8-in. size
		1.9	1.64	1.64	1.58			- - Ratios of Adjacent Values
4.0	—	0.16	0.28	0.39	0.52	—	—	( ) Tons/Hr/gpm
		(.008)	(.009)	(.0097)	(.010)			
		(.012)	(.0120)	(.012)	(.0124)	(.012)		
5.5	—	0.24	0.36	0.50	0.62	0.74	0.86	Tons per Hour of Limestone 5/8-1 1/8-in. size
		1.6	1.38	1.4	1.28	1.28		- - Ratios of Adjacent Values
4.0	—	0.15	0.26	0.36	0.47	0.58	—	( ) Tons/Hr/gpm
		(.0075)	(.0086)	(.009)	(.0094)	(.0096)		

TABLE 25

Effect of Slope upon Carrying Capacity

Slope Percent	Water Required, in gpm. 10	20	30	40	50	60	Legend
	(.017)	(.0205)					Legend: Tons per Hour of Hematite 0-1/16-in. size
5.5	0.17	0.41	—	—	—	—	- - Ratios of Adjacent Values
	2.1	2.15	—	—	—	—	( ) Tons/Hr/gpm
4.0	.08	0.19	.31	.43			
	(.008)	(.0095)	(.0103)	(.0107)			
	(.010)	(.010)	(.010)	(.0102)			Tons per Hour of Hematite 1/16-1/4-in. size
5.5	0.10	0.20	0.30	0.41	—	—	- - Ratios of Adjacent Values
			1.5	1.46			( ) Tons/Hr/gpm
4.0	—	—	0.2	0.28	0.36	—	
			(.007)	(.007)	(.0072)		
	(.006)	(.006)	(.0066)	(.007)	(.007)	(.007)	Tons per Hour of Hematite 1/4-5/8-in. size
5.5	.06	0.13	0.20	0.26	0.33	0.40	- - Ratios of Adjacent Values
				1.04	1.06		( ) Tons/Hr/gpm
4.0	—	—	—	0.25	0.32	—	
				(.0063)	(.0064)		

carrying-capacity of water and water requirements are summarized in Table 21 for a 5.5 percent slope, and in Table 22 for 4.0 percent slope. As indicated, 2.65 tons of coal of 1/4-5/8-in. size can be transported with 30 gpm of water on 5.5 percent slope, whereas, only 0.46 tons of limestone or 0.2 tons of hematite, of the same size, can be transported with the same amount of water. This indicates that 13 times as much coal as hematite can be flumed under these conditions.

The carrying-capacity ratio between 0-1/16-in. size limestone and hematite is 1.83 at 20 gpm, whereas, that between the same materials of 1/4-5/8-in. size is about 2.3. This indicates that the effect of specific gravity decreases with a decrease in particle size. Heavy materials, like hematite, can easily be transported when they are ground to very fine sizes.

Effect of Slope:

The slope of the flume also plays an important role in the transportation of solids. As a rule, the water requirements decrease as the slope of the flume increases. As before, the carrying capacity of water increases as its flow rate is increased.

These data are summarized in the Tables 23, 24, and 25 for coal, limestone, and hematite, respectively, on 5.5 percent and 4.0 percent slopes.

Coal:

The transportation ratio of 1/16-1/4-in. coal at 40 gpm of water is 3.2, for the 1/4-5/8-in. size it is 2.15, and for 5/8-1 1/8-in. size it is 1.4 when the flume slope is changed to 5.5 percent from 4.0 percent. This indicates that flume slope has a lesser affect upon flow rate of larger particle sizes.

Limestone:

The transportation ratio for fines between 5.5 and 4.0 percent flume slope is about 1.9 at 30 gpm of water. This is reduced to about 1.6 for medium coarse size and for coarse size it is changed to 1.38, which is similar to the behavior of coal. In the case of the above fines, about 90 percent more of the material can be conveyed by increasing the slope by 1.5 percent with the same amount of water. This signifies the strong influence of slope upon the transportation of small particles.

Hematite:

Hematite responds in a similar manner on 4.0 and 5.5 percent slopes. A 1.5 percent increase in flume slope, increases the carrying capacity of water by more than 100 percent. This is reduced to 50 percent for medium size fines at 20 gpm of water (Table 25).

All these examples indicate that an increase in flume slope

increases the solids carrying capacity of water. This effect decreases with increased particle size and increased specific gravity of the solids.

Concentration:

The water requirements vary with the type and size of materials and with flume slope, but in general, the optimum results can be obtained for slurries of about 30 percent (by weight) concentration of solids.

As mentioned above, a number of factors influence the transportation of slurries and they should all be considered together. As these factors are so intrinsically interrelated, it would be advisable to resort to pilot testing before any major industrial flume installations are attempted. The data presented herein may be used for preliminary selection of the model layout, but the pilot results may be more appropriate for designing the final set-up to suit specific production requirements.

Water Flow Rate:

The carrying capacity of water increases as the flow rate is increased, but reaches a maximum and apparently remains constant (Figure 46) even with an increased flow rate.

Analysis

It has been shown (p. 35) that Durand's formula, which relates all significant factors that influence the flow of slurries in pipelines, is applicable to the transportation of solids-water mixtures in open flumes. That is, the laws which govern the "established" flow of slurries in open flumes are adequately combined in a single mathematical expression to facilitate the design of a commercial installation. However, in a hydraulic mining operation, it is necessary to flush the solids into a flume before the flow condition can be established. This normally requires considerably more water and, therby, governs the solids concentration of the slurry after a constant flow regime is developed in the flume.

The purpose of this thesis was to investigate the parameters involved in transfering broken mine products into an open flume and to derive information which may be helpful in designing a complete flume system for a mining operation. As the following data indicate, this goal has been achieved, at least to the extent of satisfying the needs of a pilot installation. These data, plus the expression offered by Durand, should be sufficient to permit a reasonable mine flume design. A theoretical example is presented to demonstrate the applicability of these findings.

Example of Open-Flume Design

Assumed Data:

Material- Coal

Size- 0-1/2-in.

Required production- 100 tph

Flume Slope and Water Velocity:

Slope- 4.0 percent (25), p. 36.

Velocity- 4.5 fps (25), p. 35.

Water Volume:

Gpm- 1665 (Figure 29)

Flume Area and Cross-Section:

$$\frac{100 \times 2000}{62.4 \times 1.32} = 24300 \text{ ft}^3 \text{ of coal/hr.}$$

$$\frac{1665}{7.481} = \text{ft}^3 \text{ of water/min.}$$

$$= \frac{1665 \times 60}{7.481 \times 1} = \frac{99000}{7.481} = 13350 \text{ ft}^3 \text{ of water/hr.}$$

Therefore, total slurry = 24300 + 13350 = 37650 ft^3/hr.

Cross-Sectional Area of Flume:

$$= 37650 \text{ ft}^3\text{/hr.} \ \frac{1}{4.5 \times 3600} = 2.33 \text{ ft}^2$$

Therefore, area = 2.33 x 144 = 334.5 in^2

Optimum Shape, Taken From p. 33.

$$\text{Wetted perimeter} = 20 + 14.35 + 14.35$$
$$= 48.70\text{-in.}$$

$$\text{Therefore, } R = \frac{\text{Area}}{\text{Wetted Perimeter}} = \frac{334.5}{48.70} = 6.87\text{-in.}$$

and the ratio of R to the depth of flow $= \frac{6.87}{12} = .573$-in.

which is near the recommended value.

The resulting flume cross-section would then be as shown in Figure 47.

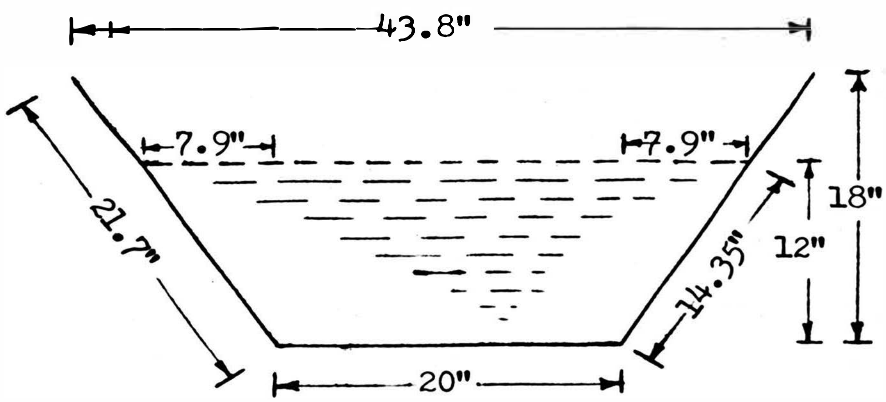

Figure 47. Cross-Section of the Designed Flume

The conditions presented in the Tables 4 through 25 would be valid only when the solids are already on the steel surface. In a mine, when the bottom material would be rocky (i.e. sandstone or clay), the amount of water required would be greater due to increased friction. When the mine products are stationary, it requires more water to accelerate and transport them than when

they are in the motion. The water requirement is further reduced when conveying moving solids within a flume. Theoretically, about 1/3 the amount of water is required to convey slurries in a flume as compared to that required for flushing the same material into the flume.

CONCLUSIONS.

A number of tests were conducted to observe the affects of particle size, specific gravity, and concentrations of various mine products, upon the water requirements for transporting slurries in open flumes. The resulting data were analyzed and the following conclusions derived:

1. An increase in particle size decreases the solids-carrying capacity of water. However, this effect decreases as the flume slope decreases and the solids density increases.

2. An increase in particle specific gravity decreases the solids-carrying capacity of water. This effect decreases as the particle size increases and the flume slope decreases.

3. An increase in flume slope increases the solids-carrying capacity of water. The effect decreases as the particle size and the particle density increase.

4. An increase in the rate of water flow increases the solids-carrying capacity of water. This effect decreases with decreased flume slope and an increase in particle density.

5. The critical velocity for 0-1/2-in. coal on 4.0 percent slope, at 40 percent concentration is 3.72 fps by Durand's formula. Reddy, from his experimental data for similar conditions, has interpolated the critical velocity to be 4.15 fps. However,

looking at Reddy's graph, it is noticed that the theoretical and experimental velocities could be equal. Therefore, Durand's formula can successfully be used to calculate the critical velocity for transporting solids in open flumes.

6. Conveying of ore by open flumes is a convenient and economical method of transportation under favorable conditions.

RECOMMENDATIONS

Based on the experiences encountered during this experimentation, it is believed that the following recommendations may be helpful to future investigators who will be concerned with slurry flow:

1. A method for introducing ore into the flume, while water is flowing at a constant velocity, should be developed.

2. Friction factors for various sizes of solids and concentrations should be studied.

3. The effect of fines on the velocity of slurry should be studied.

4. The effect of sharp bends and curves on the velocity should be studied.

5. Transportation phenomena of very fine particles (below 8 mesh) should be studied.

6. Pilot testing is recommended before installing a commercial flume for the transportation of ore.

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