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CONCRETE STOPPINGS IN COAL MINES FOR RESISTING EXPLOSIONS: DETAILED TESTS OF TYPICAL STOPPINGS AND STRENGTH OF COAL AS A BUTTRESS

BY

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Second series—Continued.

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CONCRETE STOPPINGS IN COAL MINES FOR RESISTING EXPLOSIONS: DETAILED TESTS OF TYPICAL STOPPINGS AND STRENGTH OF COAL AS A BUTTRESS[1]

By George S. Rice,[2] H. P. Greenwald,[3] H. C. Howarth,[4] and S. Avins[5]

FOREWORD

This paper gives the details of tests to determine the design of stoppings capable of withstanding a pressure, applied to either side, of 50 pounds per square inch,[6] as required by section 104 (*a*) of the Operating Regulations to Govern Coal-Mining Methods on Leased Lands on the Public Domain, issued in 1921 and quoted on page 3. The regulations stipulated that the design for such stoppings must be approved by the United States Bureau of Standards. The engineers of that organization felt that knowledge of the strength of such structures with respect to the effect of explosion pressure in comparison with static pressure and the strength of the walls which furnish the abutments was insufficient to justify drafting specifications; therefore, tests were needed to give information upon which a rational system of design could be based. A study was then begun; and several series of tests, made by the United States Bureau of Mines and the United States Bureau of Standards in cooperation, gave information upon which are based the detailed specifications offered in a later section.

Slabs representing concrete stoppings, with and without reinforcement, were tested at the Bureau of Standards in Washington, D. C.; afterwards, full-scale stoppings were tested at the Bureau of Mines Experimental mine near Pittsburgh. It was assumed that in most coal mines the strength of the floor and roof could not be relied on, but dependence must be placed upon the strength of the coal ribs. The tests developed that the maximum strength of an unreinforced concrete stopping was obtained when it acted as a flat arch buttressed against the coal ribs; but its ultimate strength depended upon the resistance to movement offered by the coal strata against which its ends were restrained or buttressed.

The importance of this question led to investigation of the lateral compressibility and unit bearing strength of the Pittsburgh coal bed in the Experimental mine. As far as the authors know, this is the first work of the kind of which there is a record; the tests have

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[1] Work on manuscript completed March, 1931.

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[6] Pressures throughout are in pounds per square inch, except where total loads are considered. In such cases it will be specifically stated that the total load in pounds is intended.

given important results and have opened a field of research in determining not only the lateral strength of coal in place in the bed but by similar methods, with hydraulic jacks, in determining the vertical compressibility of the coal and its unit bearing strength as a pillar. The latter testing, however, has different characteristics and will require extensive research before conclusions can be reached.

The operating regulations and the tests made do not take account of stresses set up in stoppings by movements of roof, coal, or floor. Forces applied in this manner are practically parallel to the faces of the stopping, whereas those studied are applied perpendicular to the faces. In so far as pressure of the roof, coal, or floor wedges the stopping more tightly in place it will increase the pressure perpendicular to the faces thereof required to blow it out, provided, of course, that the wedging does not produce sufficient stress to cause danger of failure from that source alone.

SUMMARY OF CONCLUSIONS

The tests have shown that a concrete stopping well buttressed against solid coal ribs acts as a flat arch, and its strength is enormously increased over that which it would have if supported only as a simple beam. Such a stopping, made of plain concrete restrained at the ends only and receiving no support from the roof or floor, must have a ratio of thickness to span of 1 to 10 to just resist a pressure of 50 pounds per square inch. If additional support is obtained at the roof or floor by wedging or iron dowel pins the strength is increased again by an amount which was not determined but is considerable.

Pressures of the order of 50 pounds produced by coal-dust explosions are relatively brief, as shown by many tests in the Experimental mine; a typical curve is given in Figure 7. It appears from other research that in such instances the stresses produced in a stopping will be less than when an equal pressure is applied slowly as by compressed air or hydraulic means.

When an area of the Pittsburgh coal bed is placed in compression parallel to the bedding planes the face to which the pressure is applied deflects over the area loaded and probably to a smaller extent over adjacent areas, but this was not determined. The deflection of the loaded area is roughly proportional to the pressure up to the point at which crushing occurs. When the pressure is released the surface returns toward its original position, but the return is not complete; there is a permanent set in the coal after all pressure has been released. By repeating the cycle of application and release of pressure a stable condition can be reached under which there is no additional permanent set, and all the movement is elastic. The actual values of compression and set depend upon the pressure applied; when stable conditions have been obtained with a given pressure and the pressure is then increased, a new set of stable conditions can be obtained by a few cycles of application and release at the higher pressure. This is true whether the pressure is applied horizontally in a direction either parallel to or perpendicular to the principal cleats (the face cleats) of the coal. The tests were performed with steel pressure plates up to 12 inches square and with a maximum total load of 120,000 pounds.

The maximum load that the coal would carry—that is, its bearing strength—could be determined only with plates 2 inches square, because of the limited total load (permitted by the hydraulic jack) that could be applied. The maximum load carried was 14,000 to 15,000 pounds per square inch; at this pressure the coal yielded with a pistollike report; and continued application merely resulted in driving the steel plate into the coal, which broke out around it.

The work is being continued with larger equipment and greater loads applied laterally and vertically to the coal bed.

ORIGIN OF INVESTIGATION

Provisions for the development of minerals on the public domain were made by an act of the Sixty-sixth Congress, approved February 25, 1920 (Public, No. 146), entitled "An act to promote the mining of coal, phosphate, oil, oil shale, gas, and sodium on the public domain." This act authorized the Secretary of the Interior to divide any of the coal lands or coal deposits in the United States outside of the Territory of Alaska into leasing tracts and to offer these to qualified applicants for development under certain restrictions set forth in the act, as follows:

Section 30 provides, among other things:

> Each lease shall contain provisions for the purpose of insuring the exercise of reasonable diligence, skill, and care in the operation of said property; a provision that such rules for the safety and welfare of the miners and for the prevention of undue waste as may be prescribed by said Secretary shall be observed * * *.

Section 32 provides:

> That the Secretary of the Interior is authorized to prescribe necessary and proper rules and regulations and to do any and all things necessary to carry out and accomplish the purposes of this act * * *.

The Secretary of the Interior charged the Bureau of Mines (then in that department) with the preparation of regulations governing coal mining as authorized in section 32 of the act. The bureau's engineers (of whom the senior author of this bulletin was chief) completed this task in cooperation with mining men and other interested persons from the public land States, and the regulations were approved by the Secretary of the Interior April 30, 1921. They were published the same year under the title "Operating Regulations to Govern Coal-Mining Methods and the Safety and Welfare of Miners on Leased Lands on the Public Domain." Among the safety requirements was the following:

> SEC. 104. (*a*) All connections with adjacent mines, if not used for haulage, escapeway exits or airways, shall be sealed with stoppings which shall be fireproof and be built to withstand a pressure of 50 pounds per square inch[7] on

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[7] The selection of 50 pounds as the pressure which a stopping may resist when applied to either side was made by the conference of engineers, including representatives of various State mining departments, and was based on the general opinion of men experienced in mine-explosion investigations. The evidence at their command showed that higher pressures were rarely manifested at or near faces close to the boundaries of mines which employed good ventilation and rock dusting. It was thought that these precautionary measures would be used in coal mines subject to both State inspection and additional Government inspection under leasing requirements. Furthermore, if through some neglect in precautionary measures explosion pressures were higher in certain places it would not be likely that these higher pressures would occur at or near the faces. As a rule high pressures are found a considerable distance from the face through accumulative effects. However, on p. 46 consideration is given to specifications for stoppings designed to resist higher pressures produced by explosions.

either side, calculated by a formula or method approved by the United States Bureau of Standards.

Conferences concerning this formula or method were held by engineers of the Bureau of Mines and Bureau of Standards early in 1922. Engineers of the latter organization were willing to give a tentative method of designing such stoppings, but they wished tests to be made before a final pronouncement was issued. The tests described herein were made to give the information required. They were not completed until July, 1930.

ORGANIZATION AND ACKNOWLEDGMENTS

General supervision and planning of the work were handled by G. S. Rice, chief mining engineer of the Bureau of Mines, in cooperation with engineers of the Bureau of Standards. Several changes in personnel of that bureau occurred during the period covered by the tests. The problem was at first in charge of W. A. Slater, engineer-physicist, who was later assigned to duties in connection with the strength of dams on reclamation projects in the West. During his absence the work was handled by F. A. Hitchcock, chief, cement and concrete materials section. Slater resumed work on the problem when he returned to Washington but left the service in the spring of 1928, and the testing was carried on by D. E. Parsons, chief, masonry construction section. He was actively interested in all tests at the Experimental mine until the close of the investigation, participated in planning the various tests, and witnessed most of them.

The tests at the Bureau of Standards were in charge of F. A. Hitchcock, assisted by J. C. Oleinik, who was responsible for the preparation of the test chamber and specimens. The measurements of pressure and deflection in these tests were made by O. S. Peters of the Bureau of Standards and H. P. Greenwald of the Bureau of Mines. H. I. Smith, in charge of inspection under the leasing section of the United States Geological Survey, witnessed many of the tests and gave advice concerning conditions which probably would be encountered in constructing stoppings under the requirements of leasing regulations already cited.

Before the experiments were performed at the Bureau of Standards the first stopping—a reinforced concrete stopping designed by the Bureau of Standards—had been tested in the Experimental mine, then under the supervision of J. W. Paul, coal-mining engineer, in charge of the Experimental mine section. After he assumed other duties in 1926 H. P. Greenwald, physicist, was placed in charge of the Experimental mine section and after the testing was concluded at the Bureau of Standards, Washington, he supervised the stopping-test work, which was resumed in the Experimental mine in August, 1928. All work at the mine was carried out under the direction of H. C. Howarth, coal-mine superintendent. He was responsible for the construction of all the stoppings tested and for tests of two of them during Greenwald's absence on other duties.

The compressibility of the Pittsburgh coal bed was studied by Samuel Avins, junior physicist, who joined the Experimental mine staff in July, 1929.

FIRST SERIES OF TESTS IN THE EXPERIMENTAL MINE

STRENGTH OF VENTILATION STOPPINGS IN THE EXPERIMENTAL MINE

The Experimental mine was opened primarily for full-scale tests of the explosibility of coal dust, and it was foreseen that the stoppings used to close crosscuts would have to resist the pressure of the explosions; consequently, heavy construction was employed. The stoppings were 24 inches thick, recessed 12 inches into the floor and ribs, and doweled to the roof by two rows of five 1-inch-diameter steel rods spaced 18 inches apart longitudinally and extending 9 inches into the roof and concrete. Reinforcing was provided over the entire width and height of the concrete. The horizontal reinforcement was ⅝-inch round bars on 4-inch centers; the vertical reinforcement was ¾-inch square bars on 18-inch centers. The reinforcing was 2 inches from either face, and the ends of the bars were hooked.

Pressures recorded in subsequent coal-dust explosion tests ranged up to 127 pounds, and it was probable that higher pressures were obtained but not recorded. The actual pressure on the stoppings could not be told, as the nearest recording instruments were more than 50 feet away. However, a study of the records left no doubt that they had withstood pressures far in excess of 50 pounds, and it was probable that they had been subjected to pressures exceeding 100 pounds.

Computations made when this report was prepared and based upon commonly accepted formulas for the strength of reinforced concrete slabs indicated that these stoppings should have failed at pressures of 100 to 120 pounds, depending upon the assumptions. This did not take into consideration any additional strength that might accrue from arch action that was caused by the restrained ends and could not be computed readily. Arch effects caused by the coal ribs restraining the ends were not considered as important when these stoppings were placed as the present tests showed them to be, and undoubtedly this is responsible for their withstanding the pressures developed by explosions as well as they have.

PLAN OF TESTS

It was decided that the most convenient method of testing would be to excavate a special chamber in the Experimental mine which would have two entrances, one of which would be closed by a heavy permanent stopping pierced by a door or manhole; the second entrance would be closed by the stopping to be tested. Pressure could be obtained most easily by exploding charges of black blasting powder in the chamber. Suitable manometers were to be provided to measure the pressure, and tests would be necessary to determine whether this developed uniformly over the entire area of the stopping. It would also be necessary to determine whether the manometers recorded comparably when connected to the chamber in different ways, as would be necessary. The stopping would deflect under the pressure, and some measure of this was desirable.

PREPARATION OF TEST CHAMBER

No. 1 right butt entry off the main entry of the Experimental mine was selected as the best location for the test chamber. A passageway was excavated around a block of coal, as shown in Figure 1. The entrance at the right was narrowed to 4 feet in width and height, the floor being sloped upward from No. 1 right entry. A permanent stopping 30 inches thick was erected across this narrow passageway. It was pierced by a manhole 16 inches square, covered on the inner side by a hinged steel-plate door which made a fairly tight joint against a steel-plate frame when a rubber gasket was used. The door was pulled tight by four bolts that were screwed into it and passed through holes in crossbars which bore against the outer face of the stopping. Nuts on the outer ends of the bolts tightened the door.

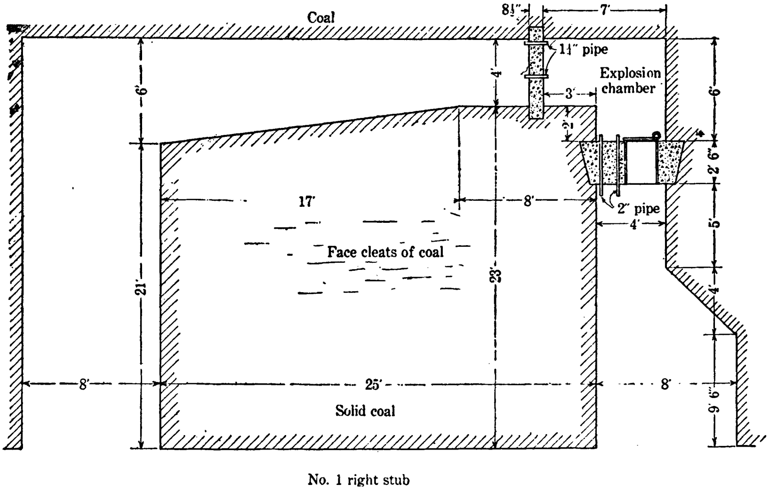

FIGURE 1.—Original stopping-test chamber in Experimental mine

The left entrance was excavated 8 feet wide and the full height of the coal bed to facilitate moving material during construction of the stopping. From the inner corner of the left entrance the passageway was narrowed and the floor sloped upward so that the area was 4 feet square at the test stopping. The chamber in which powder was exploded was 4 feet high throughout.

CONSTRUCTION OF STOPPING 1

Stopping 1 had a clear span of 4 feet, a height of 4 feet, and a thickness of 8.5 inches, was recessed 12 inches into either rib, and rested on the coal floor of the chamber, but was not fastened to the floor or roof except by friction and such bonding as may have occurred between the concrete and the coal. Figure 1 shows its position. It was considered as a beam supported at the ends only; restraint of the ends caused by the coal ribs was not considered in its design. Reinforcing, which consisted of ½-inch round bars placed horizontally and vertically and spaced 3¼ inches center to center,

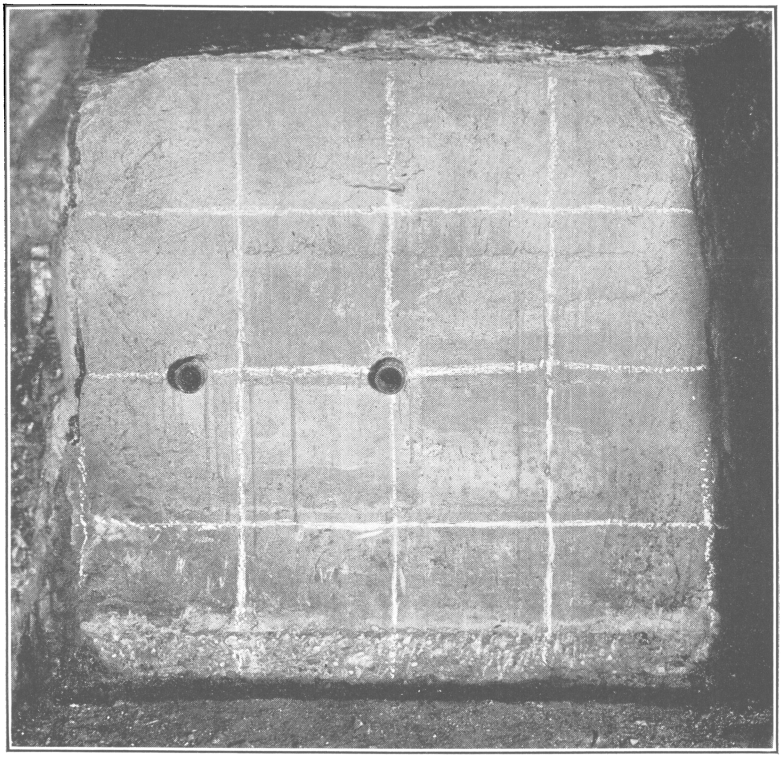

FIGURE 2.—Stopping 1 prior to test

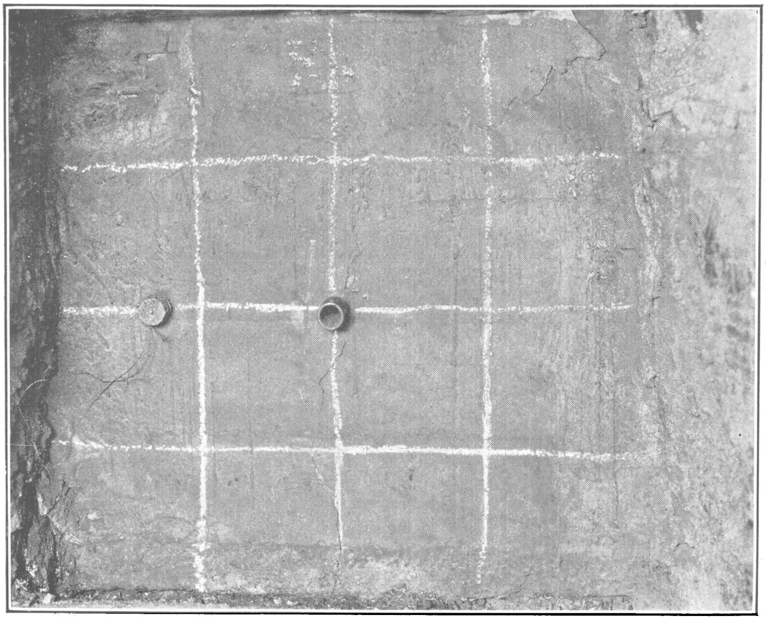

FIGURE 3.—Stopping 1 after resisting a pressure of 297 pounds. An irregular vertical crack at the middle extended from top to bottom, and other irregular diagonal cracks extended from the upper corners

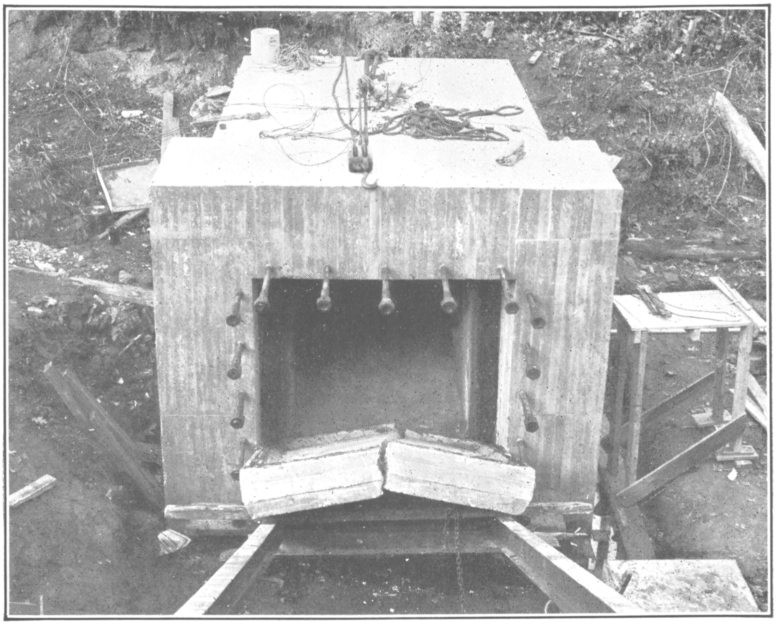

FIGURE 4.—Front of stopping-test chamber at Bureau of Standards

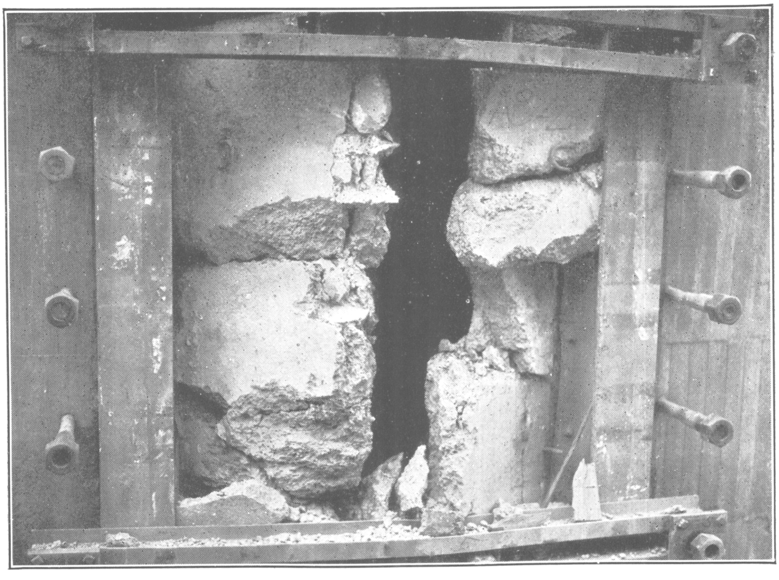

FIGURE 5.—Eight-inch plain concrete stopping with restrained ends after failure, in chamber at Bureau of Standards

was provided 1½ inches from either face. The horizontal bars extended into the recesses and were bent back on a 4-inch diameter. Diagonal crossties were placed between the reinforcement at the two faces at a number of points horizontally and vertically; the whole mass of steel was thus tied together, and although a very strong structure certainly resulted it was too complicated to be considered for mine construction. Incidentally, an error was made in reading the blue print; the vertical reinforcement should have been 12 inches center to center instead of 3¼ inches.

The mixture used was 1 part cement, 2 parts sand, and 4 parts gravel. The gravel was screened through 1-inch mesh. Only sufficient water was used to obtain a quaky consistency. The concrete was placed on July 28, 1922; on the following day the outer form was removed and all open spaces at the ribs and roof were closed with a cement gun. Figure 2 is a photograph of the completed stopping. The chalk lines on the face are 1 foot apart, and the pipes shown pass entirely through the stopping. They were used for manometer connections during the tests. Because of conflict with other work it was not possible to begin tests of this stopping until November 22, 1923, when it was approximately 16 months old.

ARRANGEMENT OF RECORDING INSTRUMENTS

Pressure was measured by two Bureau of Mines manometers placed, one each, on the permanent and test stoppings. Manometers of this type have been described in Bulletin 167.[8] They were connected to the side pipe through the test stopping and the pipe nearest the manhole through the permanent stopping. (See fig. 1.) During some of the later tests the manometer at the permanent stopping was omitted.

Tests with two manometers at a considerably later date, but with stopping 1 still in place, showed that the records they gave were unaffected by alterations in the diameter and length of the tube or pipe connecting them to the explosion chamber within limits considerably wider than the variations encountered in this test work. The records also showed that the maximum pressure was sustained long enough to preclude any difference in pressure between different parts of the chamber, consequently measurements taken at the permanent stopping could be used to give the pressure on the test stopping. Possible variation in the rate of rise of pressure at different points was less important than variations in maximum pressure.

Deflection of a point 2 inches to the left of the center of stopping 1 was magnified by a lever arrangement and recorded by a scribe on smoked paper attached to a revolving drum. This gave a time record of deflection.

The firing line to the powder charge was carried into the chamber by insulated brass rods set in a special plug screwed into the manhole door. Operation of all the instruments was controlled outside the mine, and all men were withdrawn before a test was made.

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[8] Rice, G. S., Jones, L. M., Egy, W. L., and Greenwald, H. P., Coal-Dust Explosion Tests in the Experimental Mine, 1913 to 1918, inclusive: Bull. 167, Bureau of Mines, 1922, pp. 49–51.

See also Bouton, C. M., Griffin, H. K., and Golden, P. L., Accuracy of Manometry of Explosions; Comparative Performance of Some Diaphragm-Type Explosion Manometers When Using Hydrogen-Air Mixtures: Tech. Paper 496, Bureau of Mines, 1931, 52 pp.

RESULTS OF TESTS

Stopping 1 was subjected to 18 tests, in which the pressure ranged from 14 to 161 pounds, between November 22 and 28, 1923. Special pressure heads had to be prepared for the manometers before higher pressures were employed, and because of this and the intervention of other work additional tests were not performed until May 29 and June 2, 1924. On each of these days, one test was made, in which the stopping withstood pressures of 190 and 297 pounds, respectively. A charge of 50 pounds of black blasting powder was required to produce the latter pressure. The deflection at the point of measurement, which had been only 0.001 inch at the lowest pressure, increased to about 0.30 inch at the highest pressure; the deflection was not determined accurately in the last test, as it was beyond the range of the recording mechanism.

The stopping was examined carefully after each test, and no sign of failure was seen until the pressure reached 34 pounds. At this point very fine horizontal and vertical cracks about 1½ inches long were observed radiating from a single point near the center. There was no further change until the pressure reached 70 pounds, when it was seen that the cracks were about 2½ inches long. The complete extensions of these could be seen only with a magnifying glass. No further changes were noted up to and including the test in which the pressure was 190 pounds. The final test at 297 pounds gave the first pronounced indications of failure. The stopping was cracked from top to bottom along an irregular vertical line roughly in the center, and there were a number of finer independent cracks in the two halves. A piece of concrete—roughly a quarter circle of about 1 foot radius with its center at the upper left corner—spalled off, exposing the reinforcement. Irregular cracks outlined another piece at the top in the right half which might be expected to spall off. Figure 3 is a photograph of the stopping after this test; the vertical central crack and the piece spalled off in the upper left corner are plainly seen, as well as some of the smaller cracks below it. Whatever may be said of this stopping from a general consideration of mechanics it withstood the highest pressure applied to it within the meaning of the operating regulations as regards strength; and, as regards ventilation, was a better stopping after the last test than many that are constructed in mines.

The deflection records were interesting but suffered from the fact that the permanent set after each test was not recorded; consequently, the deflection from the original position of the stopping was greater in each test than that recorded. This error was doubtless negligible with low pressures because of the heavy reinforcement, but it was possibly measurable in the last few tests. Plotting deflection against pressure gave a straight line until the pressure reached 70 pounds, when there was a sudden increase in deflection with only a small increase in pressure, indicating yielding of some kind; it may have been due to breaking of the bond between concrete and steel. The deflection then proceeded at a more rapid rate than at pressures below 70 pounds and increased more rapidly than the pressure; the curve in this range was concave up.

The higher pressures forced gas into the crevices in the coal walls and floor of the chamber, which worked its way around and under the stopping and was particularly noticeable in the last test. The floor immediately outby the stopping was broken to a depth of 5 inches, and there was an additional broken place 10 feet outby the stopping.

CONCLUSIONS DRAWN FROM FIRST TESTS IN THE EXPERIMENTAL MINE

The only definite conclusion to be drawn from these tests was that such a stopping was much stronger than would be predicted from consideration of it as a beam. Actually the stopping was reinforced like a plate or slab which would be supported on four sides. Tests of later stoppings lead to the conclusion that there may have been some support at top and bottom from friction and wedging, but the amount can not be estimated and was not considered when the tests were made. The possibility of arch action induced by restraint of the ends causing additional strength was under discussion at the time, but the engineers connected with the testing work did not reach an agreement as to its efficacy. The stopping was evidently much stronger than would be predicted by any computations made on the assumption that it was a beam supported only at the ends and without additional restraint. The requirement of resisting a pressure of 50 pounds was greatly exceeded and could evidently be met by a stopping in which the reinforcement was reduced greatly if not omitted.

TESTS AT THE BUREAU OF STANDARDS

Test work in the Experimental mine would, it was evident, be slow because of the interference of other work and the necessity of testing one stopping completely before the next could be prepared. Greater speed might be attained by preparing a special chamber in which slabs representing stoppings could be placed and tested. This method was worked out by the engineers of the two bureaus, and the chamber was constructed at the Bureau of Standards in Washington.

CONSTRUCTION OF TEST CHAMBER

The chamber was made of reinforced concrete with walls 2 feet thick; the interior was 4 feet square and 8 feet long. The rear wall was pierced by a door or manhole, and the front was open and specially shaped to receive the test specimens. Figure 4 is a photograph of the front and top of the chamber and shows a broken specimen partly removed. The method of holding the slabs in place is shown more clearly in Figure 6, which is a horizontal cross section of the front half of the chamber. The slab representing the stopping was of the desired thickness over an area exactly 4 feet square, and outside this it was thicker to provide the necessary excess strength at the bearing surface. The surface bearing against the chamber was grooved to receive a solid, round, rubber gasket thick enough to prevent the slab bearing directly on the chamber; this gasket was fastened in the groove with hot tar before the slab was placed. The space marked *A* was filled with quick-hardening cement mortar after the slab had been placed to prevent escape of the compressed gases and restrict the application of pressure to the desired area. Pressure on the slab was transmitted to fabricated-steel bearing blocks at either side through wood and plaster of Paris footings; these blocks were held in turn by a heavy grillage of steel beams fastened to anchor bolts cast into the chamber. When placed as shown the slab was supported at the ends only and not restrained. Restraint could be obtained by filling the spaces marked *X* with a quick-setting cement mortar. Provision was also made for supporting the slab at top and bottom as well as the sides in certain tests.

DESIGN OF TEST SPECIMENS

Twelve slabs representing stoppings were prepared for test. Two of these were plain concrete 8 inches thick, 2 were plain concrete 12 inches thick, and the remaining 8 were reinforced in different ways and were 8 inches thick. There were five different arrangements of reinforcement designed to resist stresses in different ways. The concrete for the specimens consisted of 1 part cement, 2 parts Potomac River sand, and 4 parts ¾-inch Potomac River gravel by volume of dry rodded materials. Water was added to each batch to give the desired consistency, and the amount was varied with the amount of moisture contained in the aggregate.

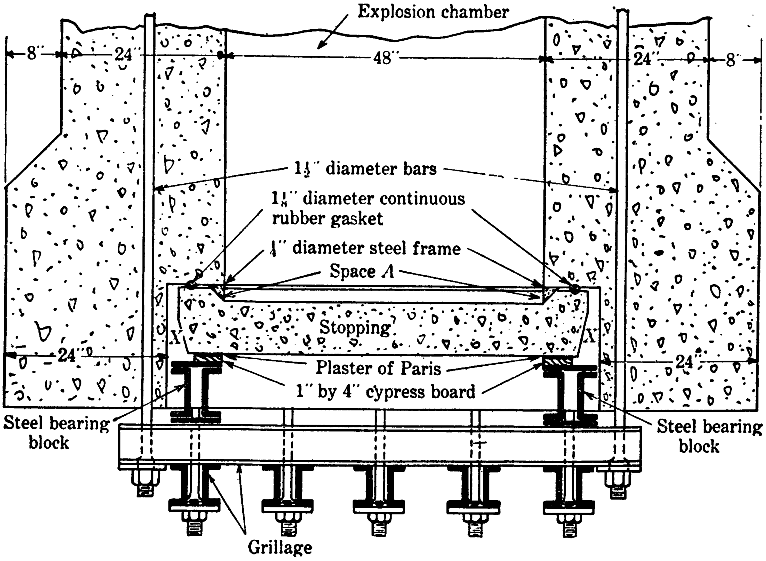

FIGURE 6.—Horizontal cross section of front half of test chamber at Bureau of Standards

Tests of the steel showed an average yield point of 50,000 pounds per square inch. Cylinders, 6 by 12 inches, were made from the concrete for each slab and crushed the day the stoppings were tested. In the main, the average strength of the cylinders for each slab that were kept in damp storage ranged from 2,100 to 2,700 pounds per square inch, with extreme values of 1,660 and 3,290 pounds.

All slabs were made during October, 1926, and were stored in the open until tested. No provision was made to protect them during cool weather, but for a few the mixing water was warmed. They were not kept damp during the aging period but were exposed to the rain and sun.

TEST METHODS AND RECORDS

Each slab was subjected to a static pressure test by means of compressed air before black blasting powder was used. The available air pressure ranged from 30 to 56 pounds. The increments in pressure caused by increasing weights of powder were rather large, and it was apparent that certain slabs might have failed with somewhat lower pressures than the maximum developed.

The static pressure attained by compressed air was measured by a gage of the common Bourdon-tube type. Three different instruments were used when black blasting powder was employed; these were a Bureau of Mines manometer, a telemeter pressure gage, and a steam-engine indicator. The Bureau of Mines manometer has been mentioned; the telemeter pressure gage measured the deflection of a steel diaphragm by means of an electric telemeter.[9] The steam indicator was used as an auxiliary device to protect against complete loss of records in case of failure of the manometer or telemeter. The manometer was obtained from the Experimental mine, and its use was discontinued as soon as comparative records showed proper agreement between it and the telemeter gage. Both the manometer and telemeter gave time records of pressure; the indicator did not.

Deflection of the slab was measured at midheight by a steel beam, which was pressed against the slab at its ends, 22 inches on either side of the center. Movements of the center of the slab relative to this beam were measured by a telemeter.

RESULTS OF TESTS

The principal data on the tests are given in Table 1.

TABLE 1.—*Data on tests of slabs at Bureau of Standards*

Designation of slab	Tensile reinforcement	Thickness	Maximum static pressure applied	Maximum explosion pressure resisted	Explosion pressure causing failure	Computed stresses	
						Modulus of rupture	Stress in steel at highest pressure resisted
	Per cent	*Inches*	*Pounds per square inch*	*Pounds per square inch*	*Pounds per square inch*		*Pounds per square inch*
A8-1	0	8	[a] 10	----------	----------	260	----------
A8-2 [b]	0	8	----------	107	146	----------	----------
A12-1	0	12	[a] 23	----------	----------	260	----------
A12-2	0	12	----------	----------	[c] 46	----------	----------
B1-1	1.0	8	20	----------	[c] 49	----------	----------
C1-1	1.0	8	----------	60	80	----------	54,500
D1-1	1.0	8	----------	----------	[c] 47	----------	----------
D1-2	1.0	8	56	44	119	----------	[d] 50,800
D1-3	1.0	8	40	50	96	----------	45,400
D5-1	0.5	8	20	32	47	----------	56,100
E1-1 [b]	[e] 1.0	8	----------	50	94	----------	42,700
FC-1	[e] 1.0	8	47	41	----------	----------	[d] 43,100

[a] Stopping failed at this pressure.

[b] Stopping A8-2 had restrained ends, and stopping E1-1 was restrained on 4 sides; all others were tested as simple beams.

[c] Stopping failed in first explosion test.

[d] Stress at maximum static pressure.

[e] Stoppings E1-1 and FC-1 had 1 per cent vertical reinforcement in addition.

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[9] McCollom, B., and Peters, O. S., A New Electrical Telemeter: U. S. Bureau of Standards Technol. Paper 247, 1924, 40 pp.

The combined letter and number assigned to the slab was related to the method of reinforcing; the number after the hyphen indicates whether one or more duplicate slabs were made; thus, there were three slabs of form D1. The designs were made to give a considerable range in the ratios of resistance to shearing and tensile stresses. If static pressure was used, it was applied first, followed by explosion pressure, except, of course, when the static pressure caused failure. There is considerable difference between the maximum explosion pressure resisted by any one slab and the pressure which broke it; but this is due to the large increments of pressure used in the explosion-test work.

For the purposes of the present paper greatest importance attaches to the results obtained with slab A8–2, which was tested in November, 1926, with restrained ends; that is, space *X* in Figure 6 was filled with a quick-setting cement mortar. It resisted a pressure of 107 pounds and broke with a pressure of 146 pounds. This stopping might have failed at a somewhat lower pressure, as the manometric record showed that the pressure was still rising rapidly when rupture occured. The failure was due to rupture of the concrete in compression, but the bending movements and stresses were indeterminate because of the restraint. The pressure was sufficient to blow out much of the crushed concrete, as shown in Figure 5, a photograph after part of the grillage had been removed.

The table shows that restrained slab A8–2 withstood a pressure roughly 11 times as great as that which caused failure of slab A8–1; the latter was its exact duplicate in construction, but was tested as a simple beam. Also, the pressure resisted by slab A8–2 is greater than the pressure that caused failure of any of the others save slab D1–2, the failing pressure of which is open to question because of the wide gap between it and the highest pressure it withstood—56 pounds static.

The explosion which caused the failure of slab A8–2 also caused a vertical crack in the upper wall of the chamber approximately in line with the interior face of a vertical side wall and extending 2 feet from the face of the open end of the chamber. This crack was one-thirty-second of an inch wide, and it was evident that the reinforcement had been strained beyond the yield point. Computations made it appear that a total thrust of about 377,000 pounds was required to produce this effect.

The important finding in these tests is the great increase in strength caused by restraining the ends of the slab, which in effect changed it from a beam to a flat arch. The restrained slab was possibly 12 times as strong as the one not restrained.

The reinforced slabs gave some idea of the relative effect of static and explosion loads. Other research[10] has shown that the stresses plain and reinforced concrete will resist, when subjected to continuously increasing loads, are greater the more rapid the rate of loading or the shorter the duration of the load. Also, with rapid loading under a single impulse of pressure the inertia of the slabs may tend to lessen appreciably the effective bending moments. The effect of the latter factor was probably negligible in these tests. The moduli

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[10] Abrams, D. A., Effect of Rate of Application of Load on the Compressive Strength of Concrete: Proc. Am. Soc. Test. Mat., vol. 17, 1917, Part II, p. 364.

of rupture computed from the explosion tests were considerably higher than those computed for slabs that failed under static pressure; again, the pressures that caused failure were higher than those computed as required to cause failure under conditions of static load. This was taken as evidence that stoppings whose design was based on static pressures would be amply safe when subjected to the pressures caused by explosions of gas or coal dust.

CONCLUSIONS DRAWN FROM TESTS AT THE BUREAU OF STANDARDS

The tests at the Bureau of Standards indicated:

1. The strength of a concrete stopping was increased enormously when the ends were restrained so that arch action was present and the crushing strength of the concrete was brought in play.
2. Because of the difficulty and expense of placing reinforcement properly under mining conditions it would probably be much cheaper to build plain stoppings and to rely on end restraint to obtain the specific resistance against explosion pressures demanded by the leasing regulations.
3. The pressure of an explosion similar in development to that given by a charge of black blasting powder would cause no greater stresses in a stopping than an equal pressure applied slowly; hence, designs based on static pressures were safe in so far as a difference in manner of loading was concerned.

From the evidence in hand it was concluded that stoppings in coal mines should be buttressed firmly against the walls when strength to resist explosions was required; and as only the coal ribs could be safely relied upon the next phase of the investigation was to determine the actual strength of stoppings buttressed firmly against the ribs on either side of a passageway. It was concluded further that reinforcement certainly could be omitted for short spans, and the requirements for longer spans could be estimated better after further tests were made.

SECOND SERIES OF TESTS IN THE EXPERIMENTAL MINE

The damage to the test chamber at the Bureau of Standards made it impossible to continue work there, and the investigation was transferred to the Experimental mine. Six stoppings (numbered 2 to 7) were tested; they differed from one another in thickness, span, depth of recess in the coal, and manner in which they were placed. Certain test methods were common to all; thus, all stoppings were placed at the stopping test chamber off No. 1 right entry (see fig. 1) which was enlarged as required, pressure was always produced by exploding black blasting powder, and a Bureau of Mines manometer attached to the permanent stopping was used to measure the pressure. The methods of measuring deflection were developed further as the work progressed and the number and variety of records obtained were increased steadily. The changes made require the tests of each stopping to be considered separately, but before this is done the pressures developed by black blasting powder under the test conditions and their relation to pressures produced by coal-dust explosions should be noted.

PRESSURE PRODUCED BY BLACK BLASTING POWDER

The general shape of the time-pressure curves produced by the explosion of triple F black blasting powder in the test chamber was much the same in all instances. Two typical curves taken from the tests of stopping 2 are shown in Figure 7, where they are compared with pressure curves taken from the records of coal-dust explosions in the Experimental mine. The black-powder curves show a rapid rise of pressure immediately after ignition, followed by a slower rise to the maximum, then a decrease as the gases cooled and leaked out of the chamber. The rate of pressure rise and maximum pressure both increased as the weight of powder was increased, and the maximum pressure was attained in less time. When a stopping was broken the pressure fell to atmospheric instantly.

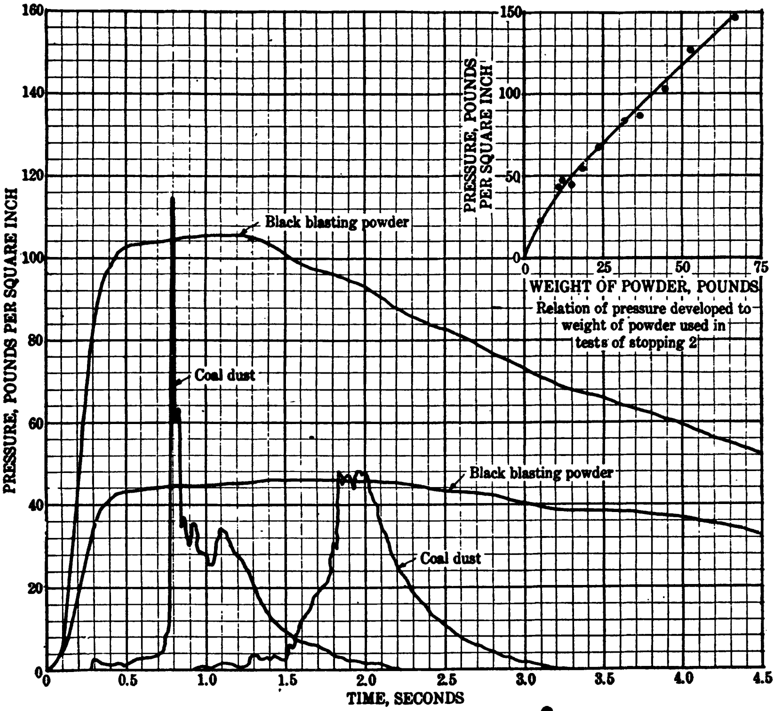


FIGURE 7.—Typical pressure curves produced by explosions of black blasting powder and coal dust

The lower curve for black blasting powder can be compared with the curve for coal dust, which gave nearly the same maximum pressure. The rate of pressure rise does not differ much in the two instances, but the pressures near the maximum were maintained much longer with the black powder. The time from ignition to maximum pressure has no significance in the coal-dust curve, as in any mine this would depend upon the distance from the point of ignition to the point where the pressure was measured and the dust conditions in the intervening space; these would determine the time required for the flame to reach the point where pressure was measured, and the high part of the pressure curve would be recorded only when the flame was in the immediate neighborhood. The explosion of black blasting powder evidently would be the more severe test of a stopping because of the longer duration of a given pressure.

At higher pressures the differences between the two types of explosions are accentuated, as comparison of the upper curves shows. It is characteristic of coal-dust explosions in the Experimental mine that high pressures are of very short duration, approaching that of impact. Thus in the curve shown the maximum pressure was 115 pounds but was above 40 pounds for less than 0.1 second. It would be possible to obtain a considerably longer duration in a large mine, but there is little probability that it could be made to approach the duration of pressure obtained in the testing chamber by the use of black blasting powder.

The quantity of powder required to produce a given pressure in the chamber depended upon the size of the latter, which was different for each stopping tested. Nevertheless, there was a close relation between quantity of powder and pressure in any given size of chamber. This is shown for stopping 2 by the graph in the upper right corner of Figure 7.

It may also be noted that the maximum pressure produced by black blasting powder in any one test in the chamber was of sufficient duration to preclude uneven pressure distribution over the stopping, even when the shape of the chamber was irregular.

DIMENSIONS AND BREAKING PRESSURES OF STOPPINGS

The principal dimensions and the pressures required to break stoppings 2 to 7 are summarized in Table 2.

TABLE 2.—*Data on stoppings 2 to 7*

Condition	Stopping						
	2	3	3A	4	5	6	7
Date of test	Aug., 1928.	Oct., 1928.	Oct., 1928.	Oct., 1929.	Dec., 1929.	Feb., 1930.	July., 1930.
Length of span feet-inches	8–0	7–8	10–0	7–7	15–7	12–8	16–3
Thickness inches	19.2	12	12	12	12	9.5	19.5
Depth of recesses do	18	18	4	6	12	6	7.7
Ratio, thickness to span	1:5	1:7.7	1:10	1:7.6	1:15.6	1:16	1:10
Ratio, depth of recess to span	1:5.3	1:5.1	1:30	1:15.2	1:15.6	1:25.3	1:25.6
Height feet-inches	7–0	7–0	7–0	7–2	7–5	6–10	6–10
Crushing strength of concrete lbs. per sq. in.	2,500	3,300	3,300	3,200	2,200	2,800	3,200
Pressure causing failure do	(1)	(2)	86	100	55	22	55

[1] Stopping 2 did not fail at a pressure of 148 pounds.

[2] Stopping 3 did not fail at a pressure of 125 pounds. The outer sides of the recesses were then cut away so that their depth was only 4 inches, and the stopping was called 3A.

All stoppings were of plain concrete; no reinforcement was used. The mixture used was the same throughout—1 part cement, 2 parts sand, and 4 parts gravel by loose volume, with only enough water to allow proper working in the form. There was also a uniform method of construction, the chamber was excavated to the proper width, the recesses were cut by hand, and the form was built. The concrete was run in with no pause other than for lunch. It was spaded continuously as it was poured, and particular care was taken to see that the recesses were filled solidly. Seven 6 by 12 inch cylinders for crushing were made to represent all the concrete used in each of stoppings 2 to 6; 10 cylinders were made for stopping 7. These were crushed in a commercial laboratory at an age of 30 days, and tests of the stoppings were started simultaneously. Air in the interior of the Experimental mine is naturally humid; indeed, the humidity rarely falls below 90 per cent and is commonly above 95 per cent. It follows that the stoppings and the cylinders which were stored near them were aged under conditions that tended to produce greater strength than the slabs tested at the Bureau of Standards.

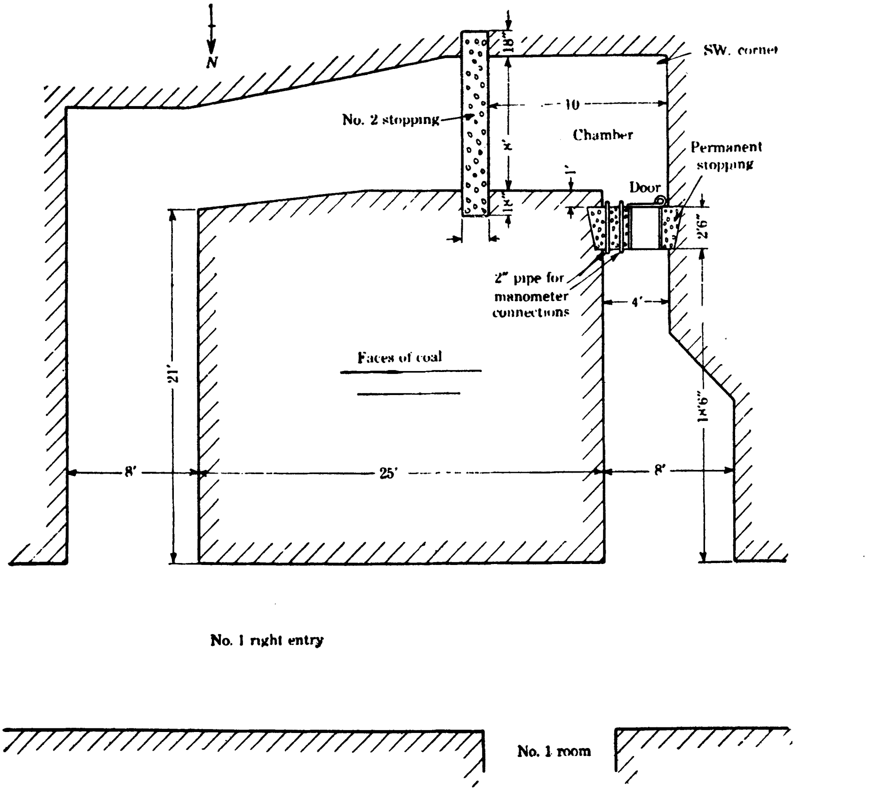


FIGURE 8.—Chamber prepared for tests of stopping 2

STOPPING 2

CONSTRUCTION

The stopping-test chamber was enlarged to the shape shown in Figure 8, which also shows the location of stopping 2. The entire height of coal was removed so that the height of the stopping was that of the coal bed plus the draw slate above it, The immediate floor under the coal is fire clay, which is firm and fairly smooth when first exposed, and the stopping was set directly on it.

This stopping had a clear span of 8 feet and was recessed 18 inches in either rib. The thickness was one-fifth the span, or 19.2 inches. No photograph was taken before the tests; but Figure 9, taken after the tests were made, gives a good idea of its appearance. The upper corners of the passageway (in the draw slate) were not cut square, and the span was somewhat less at this point; also the recesses were deeper by an equal amount as their rear surfaces were cut vertically.

Placing concrete properly against the roof is difficult, as the final form boards must be installed in short sections and the concrete rammed in horizontally. This leaves a rough surface and at the final point a small cavity which must be closed by plastering or guniting after the form has been removed. This was done with stopping 2, and the junctions of the ribs and the inner face were also plastered.

Two steel pins bored to receive the points of a strain gage were set in the concrete 16 inches apart on the horizontal center line and were located centrally as regards the span. They were used primarily to determine shrinkage during aging, but they were also used in the deflection measurements. The concrete was 48 hours old before it attained sufficient rigidity to give satisfactory readings; shrinkage of 0.0016 inch in 16 inches took place during the next 3 days, after which no further change was noted. This was 0.01 per cent or 0.013 inch in the entire length of concrete, if the shrinkage was uniform.

DEFLECTION MEASUREMENTS

There were 11 tests of this stopping; no deflection measurements were made in the first 6. A measuring device was installed before the seventh test and consisted of a thin iron bar resting against the stopping and sliding between two similar fixed bars. Movement of the stopping pushed the first bar forward, and the displacement was measured after each test. This device was placed on the floor midway between the two ribs; it does not appear in Figure 9.

For this and all later stoppings the face to which the pressure was applied was called the inner face and the opposite the outer face; thus in the present instance the device recorded the deflection of a point in the outer face. This measurement was taken from the position to which the stopping returned when the pressure was released, and there was no measurement of the permanent set. Tests of later stoppings showed that this set was considerable; the stopping did not return to its original position after any test.

A strain gage reading was taken of the aforementioned pins after each test, which gave the permanent opening of the vertical tension crack which appears at the center of the span at low loads; it is the first sign of strain in the concrete and is enlarged by each increment of pressure.

RESULTS OF TESTS

Tests were begun on August 22, 1928, and consumed 3 days. The more important data are given in Table 3.

TABLE 3.—*Results of tests of stopping 2*

Test	Powder charge	Maximum pressure	Maximum deflection	Width of central crack	Test	Powder charge	Maximum pressure	Maximum deflection	Width of central crack
	Pounds	*Lbs. per sq. in.*	*Inch*	*Inch*		*Pounds*	*Lbs. per sq. in.*	*Inch*	*Inch*
1	5	24	----------	0.000	7	31	83	0.11	0.029
2	11	42	----------	.008	8	37	87	.11	.034
3	13	46	----------	.013	9	43.5	105	.15	.037
4	15	46	----------	.015	10	55	130	.21	[1] .054
5	18	56	----------	.015	11	67	148	.27	----------
6	23	66	----------	.022					

[1] Width greater than this figure, capacity of strain gage exceeded.

DEFLECTION RECORDS

The figures in the fourth column of Table 3 show that the center of the stopping deflected considerably in each test. It always returned toward the position it had before any particular test, but measurements of later stoppings showed that this return was incomplete. The total deflection from the first position is consequently greater for any test of Table 3 than the figure given.

The central tension crack did not appear after test 1, and its width is given as zero for that test in Table 3. It appeared in test 2, opened rapidly as the pressure was raised in successive tests, and was too wide to be measured accurately after test 10.

VISUAL OBSERVATIONS

The stopping was examined carefully after each test. No alteration was noted after test 1, but a fine vertical crack was found at the center of the outer face after test 2. This crack widened perceptibly in test 3; and a fine crack 6 inches long was found in the plaster at the junction of the inner face and the south rib, showing that the stopping had been thrust forward. There was no perceptible change in tests 4 and 5, and it may be noted here that tests 2 to 5 were made to obtain as closely as possible a pressure of 50 pounds. No explanation was found for the failure to obtain a higher pressure in test 4 than in test 3.

After test 6 (pressure, 66 pounds) it was found that gases had worked under and over the stopping. A small piece of floor was blown out in front and to the right of the center thereof, and small pieces of roof were blown out at and slightly to the right of the center. In test 7 the tension crack opened perceptibly, but no other effects were noted.

Beginning with test 8 there was strong evidence of gas blowing over the stopping. Small pieces of the outer face were broken off in test 8, and additional ones spalled off in test 9. In test 10 the hot gas cut a channel through the roof, which had to be plastered shut before test 11 was made. The plaster blew out in test 11, and the channel was enlarged. The escape of gas could be heard outside the mine, sounding like distant thunder.

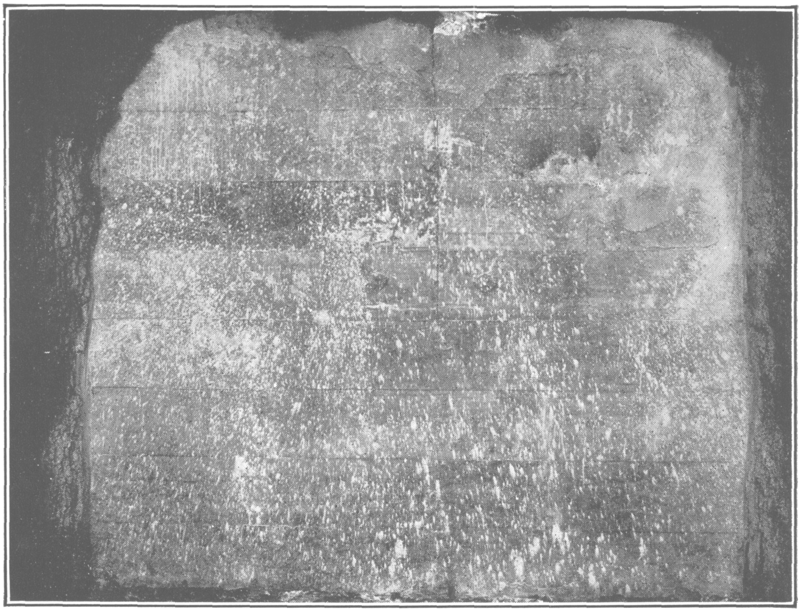


FIGURE 9.—Stopping 2 after resisting a pressure of 148 pounds

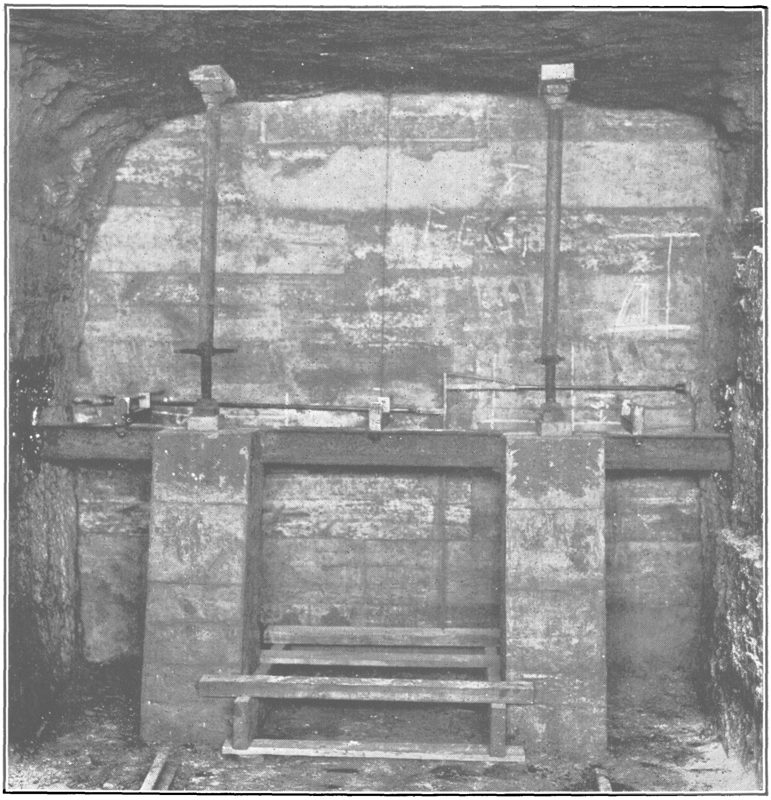


FIGURE 10.—Stopping 3 prior to test

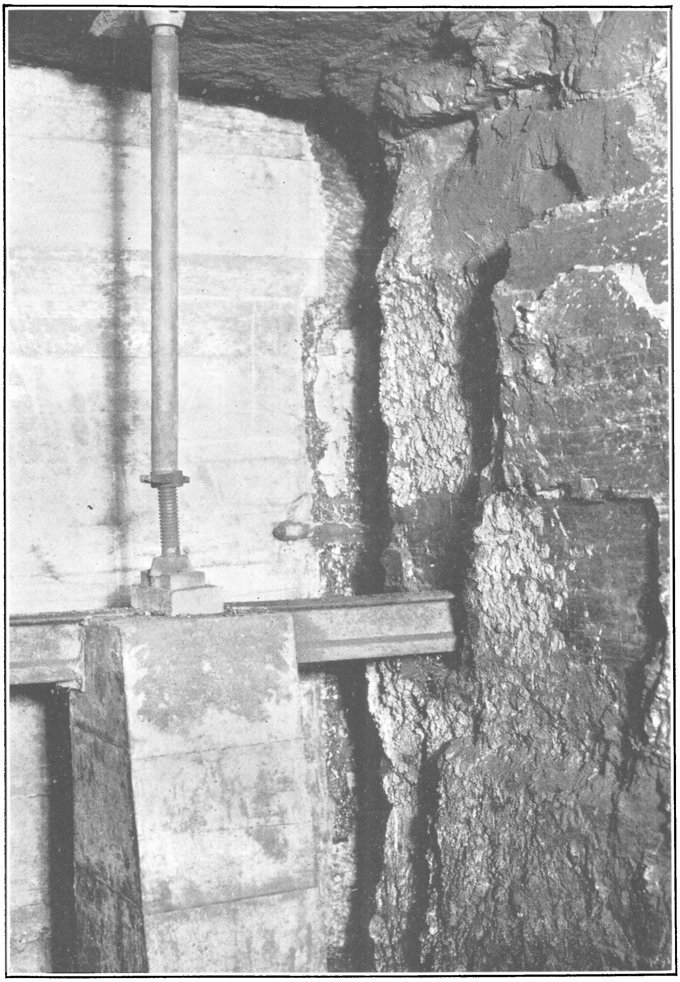


FIGURE 11.—Coal cut away from outer face of stopping 3 to relieve cantilever action

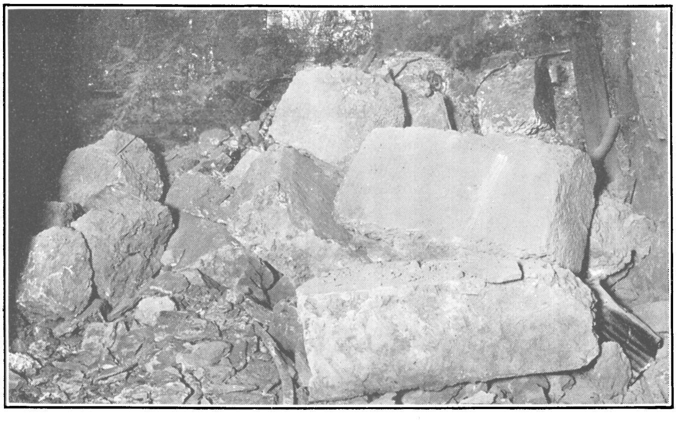


FIGURE 12.—Débris from stopping 3

The central crack was visibly wider after each test; and there was additional cracking of the plaster at the junction of the inner face and the ribs, caused by the forward thrust of the stopping. Figure 9 shows the stopping after test 11. The tension crack is visible, particularly near the roof. The blackened spots at the roof are places where gas blew over the top, and small areas can be seen where the surface has spalled. The stopping was still serviceable for ventilation, particularly if the openings at the roof were plastered shut, and it was evident that the pressure required to cause failure was considerably more than 148 pounds. Because of the difficulty of keeping the chamber gas-tight it was decided not to proceed further with this stopping, and it was broken up with dynamite.

CONCLUSIONS FOR STOPPING 2

The tests of stopping 2 proved conclusively that the strength of properly constructed stoppings was due to restraint of the recessed portion by the ribs, which was primarily buttressing of the ends by the solid coal against which they rested, to which might be added cantilever action when the recesses were deep. Reinforcement was not necessary to comply with the operating regulations, at least not for short spans, and the ratio of thickness to span could be considerably less than 1 to 5. Later tests indicated that a pressure of at least 225 pounds would have been required to demolish stopping 2.

STOPPING 3

CONSTRUCTION

Stopping 3 had approximately the same span as stopping 2, and its strength was reduced by decreasing its thickness to 12 inches. It was thought that this should be the minimum for practical operations to insure uniform concrete; there might be danger of irregularities, due to improper spading when narrower forms were filled. The stopping was placed 2.5 feet outby the location of stopping 2; otherwise the chamber was unchanged, and Figure 8 illustrates the general conditions.

The clear span at the point selected was 7 feet 8 inches; and the recesses were 18 inches deep, as before. The thickness of the concrete was 12 inches and the height 7 feet. The ratio of thickness to span was 1 to 7.7, a decrease of 44 per cent from that of stopping 2, for which the ratio was 1 to 5. Figure 10 is a photograph of the outer face of the stopping before the test and shows the deflection-measuring instruments which are to be described.

The stopping was set direct on the fire-clay floor and carried to the roof, necessitating plastering at the junction with the roof, as in the case of stopping 2. Steel pins were provided for strain-gage measurements of shrinkage. Shrinkage was complete at the end of 10 days and amounted to 0.0012 inch in 18 inches, or 0.0067 per cent, pointing to a reduction of 0.009 inch in the total length of the concrete.

The stopping resisted a pressure of 125 pounds, and it was judged that part of the strength was due to cantilever action which might be overcome by reducing the depth of the recesses. This was done by cutting away the coal ribs from the outer face only, so that the recesses were only 4 inches deep. The altered stopping was called 3A, and its clear span was 10 feet. The ratio of thickness to span was then 1 to 10. The method of making the cut in the coal is illustrated in Figure 11, a photograph of the junction of the outer face and the right or north rib. The original line left by the coal on the concrete when it was poured is clearly visible, but the new junction is concealed in the depth of the cut.

DEFLECTION MEASUREMENTS.

The methods of measuring deflection were improved and extended. Movement of the stopping parallel to the applied pressure was recorded at three points along the horizontal center line of the outer face, as shown in Figure 10. These were on and 33 inches either side of the vertical center line, respectively. Steel pins were cast into the concrete at the designated points, and the moving part of the deflection indicators was pressed against them. The indicator consisted of a round metal rod sliding with some friction through two bearings supported by a metal block. There was a vertical piece at the rear of the block, and the distance from the end of the rod to the face of this piece was measured by a spring gage and micrometer caliper when the rod was firmly in contact with the pin in the concrete before each test. The movement of the stopping pushed the rods forward and left them in the position of maximum deflection. The altered distance at the rear was measured, the rod restored to contact with the pin, and a third measurement made.

The difference of the first two readings was the maximum deflection and of the first and third was the permanent set. The indicators were supported on an inverted 60-pound steel rail cast into piers about 2 feet in front of the stopping. Additional rigidity was obtained by screw jacks between the top of the piers and the roof.

The general principle of this system was used in all tests during the remainder of the investigation, but details were altered as convenience demanded.

It was desirable to obtain some measurement of the movement of the ends of the stopping in a direction perpendicular to the applied pressure—that is, parallel to the length of the stopping. The coal was under pressure in this direction and certainly yielded to some extent. Two-inch-square steel plates were cemented against the coal at the back of the recesses close to the outer wall thereof. Pipes were fastened in place horizontally but at a slight angle with the face of the stopping, so that one end rested against the plate and the other came into the open just in front of the outer face. They were arranged so that no material could enter them when the concrete was poured. Long steel rods carried in double bearings passed down these pipes and made contact with the plates. The rods and the ends of the pipes are seen in Figure 10. The outer ends of the rods were joined by pivots to a vertical lever to magnify their motion, and a strong spring kept them firmly in contact with the steel plates at all times. The upper end of the vertical lever, its junctions with the rods, and the spring are seen plainly in Figure 10, but the lower end of the lever is somewhat out of focus. The lower end of the lever was provided with a scribe which traced a record on smoked paper. The paper and its support do not appear in Figure 10. Records of maximum deflection and permanent set were obtained.

Permanent opening of the central tension crack was obtained by strain-gage measurements, as in the tests of stopping 2.

RESULTS OF TESTS

There were six tests of stopping 3 and three of stopping 3A. Table 4 gives the primary data.

TABLE 4.—*Results of tests of stoppings 3 and 3A*

STOPPING 3

Test	Pressure	Deflection of center [1]	Set of center [1]	Compression of coal at end of stopping [1]	Set of coal at end of stopping [1]	Width of tension crack
	Pounds per square inch	*Inch*	*Inch*	*Inch*	*Inch*	*Inch*
1	62	0.205	0.053	0.031	0.012	0.024
2	67	.244	.063	.041	.015	.030
3	76	.281	.075	.047	.017	.034
4	86	.327	.087	.057	.022	.039
5	108	.449	.131	.080	.033	.054
6	125	.619	.200	.110	.048	.077

STOPPING 3A

Test	Pressure	Deflection of center [1]	Set of center [1]	Compression of coal at end of stopping [1]	Set of coal at end of stopping [1]	Width of tension crack
1	60	0.662	0.338	0.112	0.076	0.112
2	69	.800	.433	.140	.101	.135
3	[2] 86					

[1] Measured from position of stopping before first test.
[2] Stopping blown out in this test.

VISUAL OBSERVATIONS

Test 1 of stopping 3 (pressure, 62 pounds) developed the vertical tension crack at the center of the outer face. It passed about 3 inches to the right of the central deflection pin. There was slight indication of gas blowing over the stopping along the roof. Fine cracks appeared at the junction of the inner face and the ribs, caused by the forward thrust of the stopping. Tests 2 to 4 widened the central tension crack somewhat, and there was additional evidence of gas blowing over the stopping. The pressure in these tests was 67, 76, and 86 pounds, respectively, and the escape of gas could be heard at the pit mouth in the last two. Test 5 developed a pressure of 108 pounds, and the tension crack widened perceptibly. There were also two pronounced diagonal cracks across the upper north corner of the inner face; the largest of these outlined a right triangle whose perpendicular sides along the rib and roof were about 10 inches long. After test 6 (pressure, 125 pounds) a secondary vertical tension crack was found in the outer face. It started at the roof about 16 inches to the right (north) of the primary crack, extended downward irregularly to the left, and joined the principal crack 3 feet from the roof. Gas was blown over the stopping between the two cracks. The cracks in the inner face were more pronounced. A low rumbling noise was heard at the pit mouth, probably caused by the gas escaping over the stopping.

The alterations allowed stopping 3A to deflect much more than did stopping 3, and the first test (pressure, 60 pounds) opened all cracks appreciably. The inner face of the stopping evidently had swung away from the inner faces of the recesses and had not returned to its original position. The next test (pressure, 69 pounds) caused pronounced movement and an additional vertical tension crack about 1 foot to the right of the secondary crack. The diagonal cracks in the corner of the inner face gaped 0.05 to 0.10 inch after the test. There was considerable escape of gas over the stopping, and it was necessary to plaster the junction of the inner face of the stopping and the roof before the final test.

The final test developed a pressure of 86 pounds. The stopping was blown out and broken up completely. The pressure curve indicates that failure would have occurred at lower pressure, possibly less than 80 pounds, as the pressure was still rising rapidly when the stopping failed. The débris of the stopping was thrown against the rib of the entrance passageway, 30 feet distant, with such force that masses of coal and slate were dislodged. The measuring devices were destroyed and buried in the mass of broken concrete. Figure 12 is a view of the débris from the original location of the stopping. The steel rail is seen at the right jammed in the corner of the passageway.

Masses of concrete were left in the recesses in both ribs. The amount was greatest at the floor and least at the roof. The break line sloped outward in both cases; that is, there was more concrete at the inner than at the outer face of the recesses. The manner in which the concrete broke probably was influenced by cutting of the coal from the outer face. The coal was not cut away from the inner face in a similar manner, and the maximum pressure probably was not effective over as great a length as the free span of the outer face. It was also seen that the depth of the recess had been less than 4 inches at some points.

DEFLECTION RECORDS

Maximum deflection and permanent set of outer face.—The recorded deflection and set at the center of the outer face are given in Table 4. The basis of measurement is the location of the respective points before the first test; that is, before any pressure was applied. The relation of the deflection and set of the center to the pressure is shown in Figure 13. Curve *1* is the maximum deflection of stopping 3, and curve *2* is its permanent set. It is seen that both were approximately proportional to the pressure at first but increased much more rapidly at higher pressures. Similar values for stopping 3A are given by lines *5* and *6*. The deflection and set at a given pressure have been increased greatly by cutting away the coal so that the span was greater and the depth of the recesses less.

Some idea of the deflection of the entire face in a horizontal plane can be obtained by plotting the movement at the center and about 1 foot from each rib in proper relationship. The general relationship of the points is seen in Figure 10, and a horizontal cross section of the stopping in the plane of measurement appears in Figure 14. Below this the deflection and set at the three points are plotted on a scale one hundred times as great as that of the stopping to show their relationship clearly. The lines of the ribs and the ends of the concrete are also carried on this graph. The zero deflection line may be considered as the outer face of the concrete before the first test. Line *1* is the position of stopping 3 after test 2 (pressure, 67 pounds), and line *4* is the position after the pressure was released in this test. The first is maximum deflection and the second is the set. Similarly, lines *2* and *5* give the deflection and set after test 6 (pressure, 125 pounds). The various lines have been extrapolated to meet the boundaries of the graph. Lines *1*, *2*, *4*, and *5* converge to a common point on the zero deflection line in the south half of the stopping, indicating that cantilever action was present, as there was about 1 foot of concrete to the left or south thereof. It should be noted that straight lines have been drawn only because two points allow nothing else. Tests of later stoppings showed that the two halves of the stopping were bowed slightly, as any beam would be when under a uniform load. Furthermore, if cantilever action was present, the

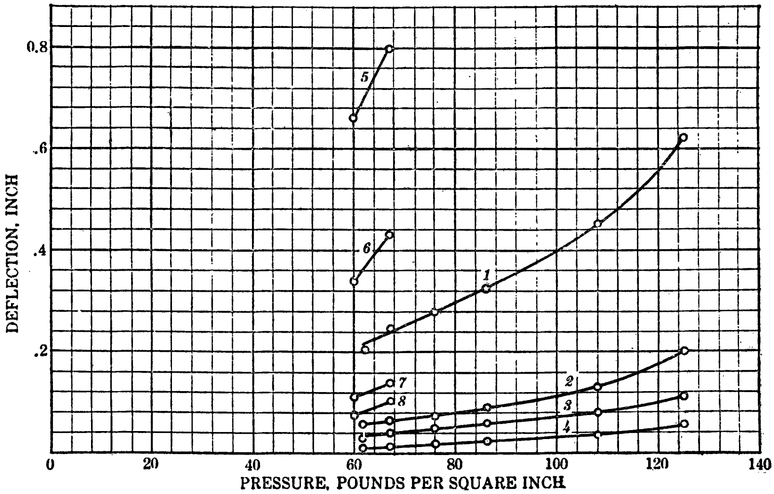
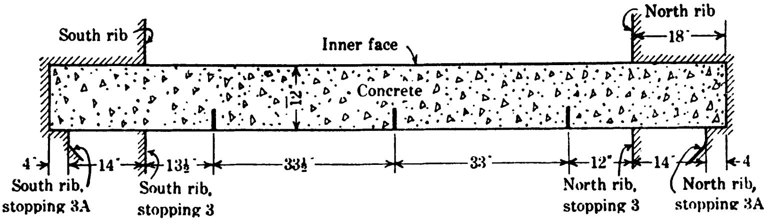


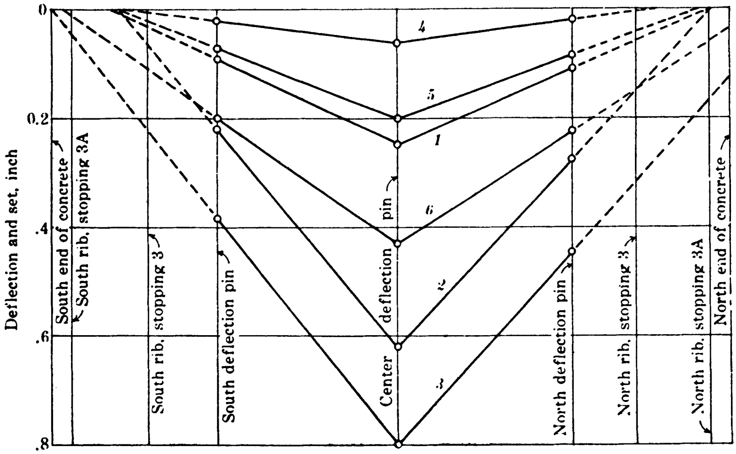
FIGURE 13.—Deflection of center of span and compression of coal ribs, stoppings 3 and 3A

Curve	Stopping	Designation
1	3	Maximum deflection, center of span.
2	3	Permanent set, center of span.
3	3	Maximum compression, one rib.
4	3	Permanent set, one rib.
5	3A	Maximum deflection, center of span.
6	3A	Permanent set, center of span.
7	3A	Maximum compression, one rib.
8	3A	Permanent set, one rib.

halves were bent in the opposite direction at the supports, and the deflection lines would come in tangent to the zero deflection line instead of intersecting it at an angle. These differences are appreciable when the proper measurements are made carefully, but the errors in the present case are not sufficient to invalidate the conclusion that cantilever action was present in the south rib.



HORIZONTAL CROSS SECTION OF STOPPING



DEFLECTION AND SET OF OUTER FACE IN HORIZONTAL PLANE

FIGURE 14.—Movement of outer face of stoppings 3 and 3A

Curve	Measurement	Stopping	Test	Pressure, lbs. per sq. in.
1	Deflection	3	2	67
2	do	3	6	125
3	do	3A	2	69
4	Set	3	2	67
5	do	3	6	125
6	do	3A	2	69

Conditions in the north half of the stopping were somewhat different. The four lines do not meet at a common point, although three do fairly well. This intersection is only 4 inches from the north end of the concrete, only one-third the distance found in the south half. It is logical to infer that cantilever action was less marked, and the two halves certainly did not have similar behavior.

Lines *3* and *6* give the deflection and set in test 2 of stopping 3A, in which the pressure was 69 pounds, approximately the same as in test 2 of stopping 3. Comparison of lines *1* and *3* shows that conditions were greatly altered. The south half of stopping 3A pivoted at the end of the concrete and at the center deflected over three times as far as did stopping 3. Extrapolation of the north half of line *3* intersects the north end of the concrete at a deflection of 0.13 inch; apparently the whole mass of concrete was thrust forward, compressing the coal before it. Line *6* shows that it did not return to its original position. There was permanent set over the entire north half of the stopping, which was not present in the south half, as line *6* intersects the zero deflection line close to the end of the concrete, and one may assume safely that translational movement of this end was insignificant.

Compression of coal at end of stopping.—The device used to give the end thrust of the stopping (previously described) recorded the sum of the movements at the two ends. The two halves behaved differently; and the movement of the two ends was probably somewhat different, but there was no way of determining this. The values in Table 4 are one-half those recorded for the two ends. The end deflection and set have been plotted against the pressure in Figure 13 as curves *3* and *4*, for stopping 3, and *7* and *8*, for stopping 3A. End movement was much less than movement of the face, as would be expected, but all the curves have the same general shape. It is difficult to interpret these records, because the movement of the end of the concrete is probably a combination of rotation and translation. The matter is discussed in more detail in the consideration of the tests of stopping 4 where movement of the two ends was measured separately.

Width of central crack.—The width of the central crack is given in the last column of Table 4. It increased in much the same manner as the deflections and permanent sets, and in the first three tests of stopping 3 it was exactly equal to the sum of the set of the two ends of the stopping. Beyond this point the end movement increased more rapidly, and the equality was lost. The curve of width of central crack versus pressure would fall between curves *3* and *4* if plotted in Figure 13.

CONCLUSIONS FOR STOPPING 3

The primary conclusions drawn from the tests of stoppings 3 and 3A were that cantilever action was present in the former and the depth of the recesses had to be reduced considerably to avoid it. A depth of 6 inches was the minimum that could be used without causing too great pressure on the outer wall thereof from the direct thrust of the stopping, and this depth was not sufficient to restrain the concrete as a cantilever. It was also certain by analogy that part of the strength of stopping 2 was due to the deeply recessed ends.

Direct comparison of stoppings 2 and 3 was not possible, as neither broke. The change from stopping 3 to 3A increased the span and removed the cantilever action, and it was not possible to analyze the change caused by altering two variables.

The important lesson was to avoid deep recesses in the test work, to simplify conditions, and to use them in practical construction as a factor of safety.

STOPPING 4

CONSTRUCTION

Stopping 4 was designed to be a duplicate of stopping 3, except for the depth of the recesses, which was reduced to 6 inches to avoid cantilever action. It was 2.5 feet in front of the position of stopping 3, and the inner face was then about 15 feet from the rear wall of the chamber. It was necessary to cut the south rib to obtain the desired span; the need for this can be seen by referring to Figure 8 and considering the stopping shown therein as moved 5 feet farther from the rear wall of the chamber. When the changes were made it was found that the clear span of the stopping was 7 feet 7 inches, and with a thickness of 12 inches the ratio of thickness to span was 1 to 7.6 as compared with 1 to 7.7 for stopping 3. The recesses were 6 inches deep, and the height of the stopping was 7 feet 2 inches. The fire-clay floor had been broken badly by the previous tests, and it was necessary to remove all the loose material. There was then a hollow at the center of the entry. A concrete base somewhat wider than the thickness of the stopping was placed and troweled smooth. After it had hardened for several days the surface was greased well and the form for the stopping built on it. The concrete was carried to the roof as before. The steel pins for measurement of shrinkage were set in the inner face so that they could be used to determine the permanent compression thereof after each test. Shrinkage during aging was complete at the end of 14 days and amounted to 0.0010 inch in 19.25 inches, or 0.0052 per cent of this length, which was equivalent to 0.0054 inch in the total length of the concrete. Figure 15 is a photograph of the stopping before the first test and shows the recording instruments. The first test was made on October 10, 1929, at an age of 30 days.

DEFLECTION MEASUREMENTS

Deflection of the outer face was measured at five points on the horizontal center line, at the center, about 3 inches from each rib, and midway between these points and the center. The devices appear in Figure 15 and were supported as before, except that an H-beam was substituted for the steel rail. The design of the devices was altered, a block was fastened to the sliding rod between the bearings, and the movement was measured between the end of this block and one of the bearings. The arrangement can be seen in Figure 15. The devices at the center of the stopping and on either side thereof were arranged to give a time record of movement. The upper surface was an assembly of thin brass strips set on edge with insulating material between. There was a fixed contact point bearing on the block; and as it moved an electric circuit was made and broken, as the contact point was alternately on the brass strips and the insulating pieces. This circuit was connected to a chronograph in the observatory outside the mine, and a time record was obtained thus.

An attempt was made to analyze end movement of the stopping. Steel bars imbedded close to the ends of the concrete projected 12 inches into narrow recesses cut in the ribs. The arrangement is

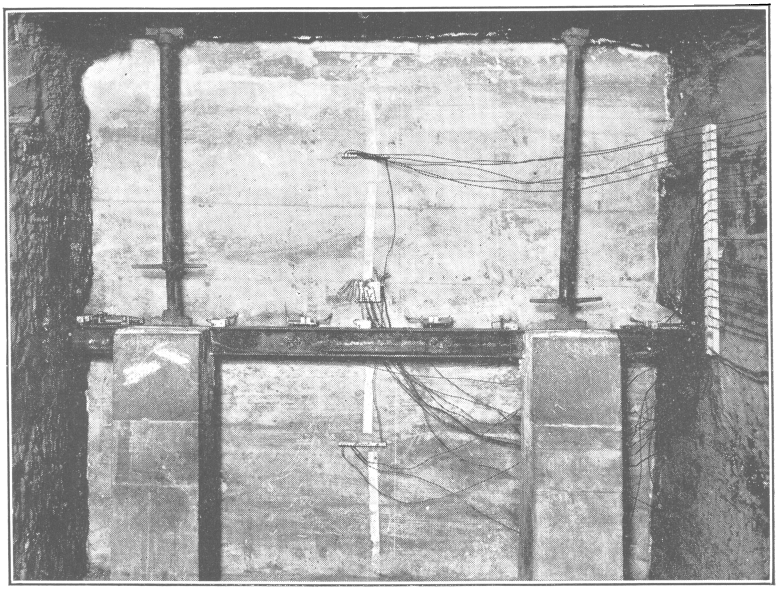


FIGURE 15.—Stopping 4 prior to test

FIGURE 16.—Steel bar set in end of stopping 4 to measure end movement

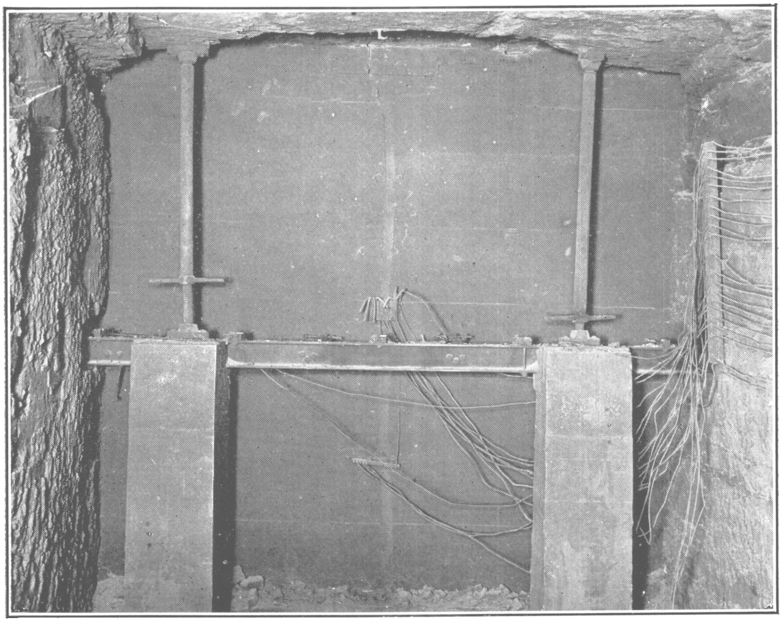


FIGURE 17.—Outer face of stopping 4 after third test

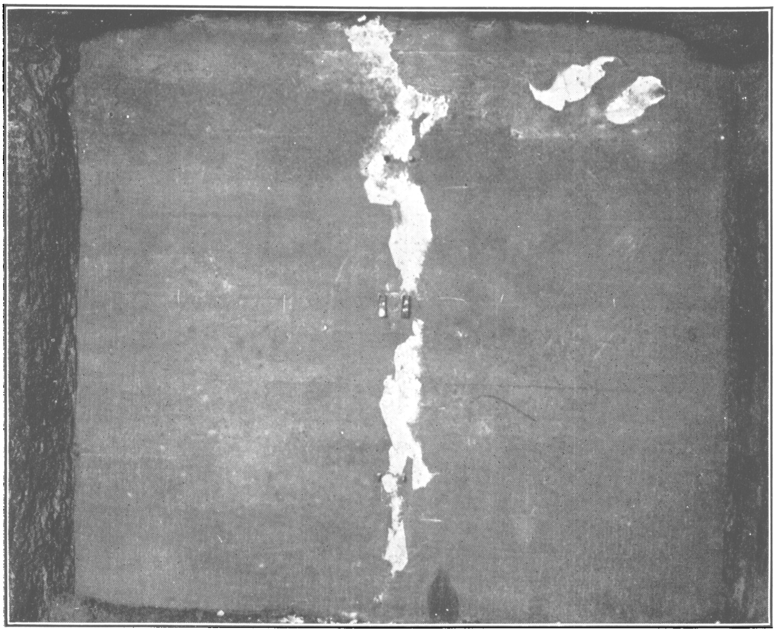


FIGURE 18.—Inner face of stopping 4 after third test

shown in Figure 16, a photograph taken at the south rib. Rods were fastened at right angles to this bar 1 and 11 inches from the outer face of the stopping and connected to deflection-measuring devices. If there was rotational movement, the record at the outer point would be greater than at the inner point, and it would be possible to determine the amount thereof if the center of rotation could be determined from the other records.

The width of the vertical tension crack and the movement of the concrete on either side thereof parallel to the face of the stopping were measured by deflection devices which appear in Figure 15 immediately on either side of the center. It is seen that these were at right angles to those measuring the deflection of the face parallel to the applied pressure. The sum of the movement on either side gave the width of the crack; moreover, the devices gave the maximum width when the stopping was under pressure, whereas previous records gave only the width after the pressure was released.

An attempt was made to measure the depth of the tension crack. This could be done by means of electrical conductors set in the concrete in such manner that they would be broken when the crack formed; but there was doubt as to the most suitable type of conductor as it would have to be insulated completely from the concrete. Fine enameled-copper wire would be suitable if a proper bond to the concrete was obtained; if not, the ductility of the wire would prevent its breaking properly. No. 30 enameled-copper wire was stretched on two frames at 2-inch intervals, and the frames were imbedded in the concrete as it was poured. These frames were about 20 inches from the roof and floor; their outer ends can be seen in Figure 15. The wires were brought to separate binding posts on one side and to a common binding post on the other. The circuits were completed through pens on the chronograph in the observatory.

A second device for the same purpose was a set of glass tubes containing conducting liquids. The tubes had thin walls and were etched on the outside so that the concrete could obtain a bond. It was believed that the brittleness of the glass would cause the tubes to break when the crack opened, the liquid would run out the crack, and the circuit would be broken. Mercury was the ideal liquid for the purpose, but it might not run out a fine crack because of its high surface tension. For this reason only half the tubes were filled with mercury and the remainder were filled with dilute sulphuric acid. Platinum wires were dipped in the acid and were soldered to copper wires to complete the circuit. These wires ran through small rubber tubes, which served the additional purpose of venting the gases liberated when current was passed. The whole set of tubes was mounted in a suitable frame and imbedded in the concrete when it was poured. The end of the frame appears in Figure 15 at the center, just above the H-beam.

If inserts of this character are to have any value, the tension crack must pass through them, and metal inserts were placed to form the crack along the desired line. These were pieces of sheet metal bent in an angle. One leg of the angle was nailed to the form and the other leg projected about 1 inch into the concrete. The leg originally fastened to the form appears as a vertical strip in Figure 15.

RESULTS OF TESTS

There were three tests of stopping 4. The primary data are given in Table 5.

TABLE 5.—*Results of tests of stopping 4*[1]

Condition		Test	
	1	2	3
Pressure ... lbs. per sq. in.	42	98	100
Deflection of center ... inch	.201	.562	.723
Set of center ... do	.076	.197	--------
Deflection of bar in south end, 1 inch from stopping ... do	--------	.115	.109
Deflection of bar in south end, 11 inches from stopping ... do	.002	.143	--------
Deflection of bar in north end, 1 inch from stopping ... do	.036	.104	.207
Deflection of bar in north end, 11 inches from stopping ... do	.028	.156	--------
Set of bar in south end, 1 inch from stopping ... do	.017	.043	.053
Set of bar in south end, 11 inches from stopping ... do	.000	.043	--------
Set of bar in north end, 1 inch from stopping ... do	.018	.045	--------
Set of bar in north end, 11 inches from stopping ... do	.000	.062	--------
Maximum width of central tension crack ... do	.064	[2] .10	[2] .43
Final width of central tension crack ... do	.030	[2] .09	--------
Compression of inner face in 19.25 inches ... do	.005	.019	.032

[1] All deflection measurements taken from position before first test.

[2] Estimated.

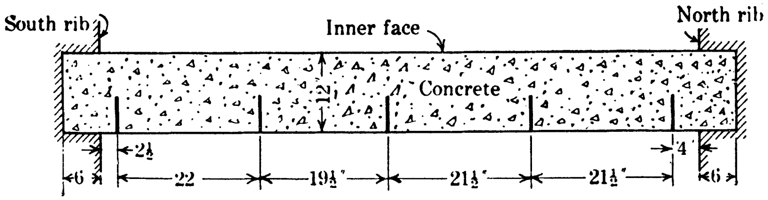
VISUAL OBSERVATIONS

The tension crack opened in the first test along the inserts placed to form it. No other signs of stress were observed. The second test increased the width of the crack and gas blew over the top of the stopping. The junction of the inner face and the roof was plastered before the third test. When the third shot was fired observers at the pit mouth heard a rumbling noise, followed by hissing; then a cloud of dust was ejected from the portal. Examination showed that gas had blown over the stopping and torn down a shell of roof, which had fallen on the instruments and damaged some of them. The end of the frame inserted nearest the roof was broken off. Figure 17 is a view of the outer face as it then appeared. The damage at the roof is apparent; the tension crack is visible near the roof. The falling material caused loss of some of the records in this test. There were three holes in the roof over the stopping, the smallest of which measured 1 by 3 inches and the largest 1.5 by 18 inches.

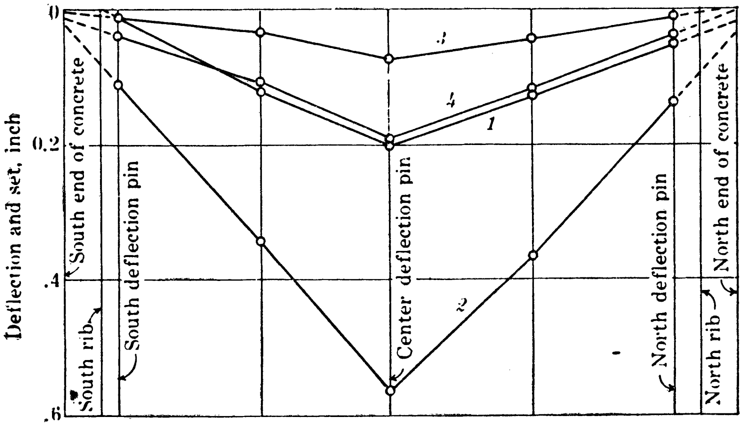
Examination of the inner face showed that the compressive strength of the concrete had been exceeded. A thin shell spalled off irregularly along the vertical center line, as shown in Figure 18; the white patches are the spalled portions. The freshly exposed concrete contrasted strongly in color with the original face, which was blackened by the products of the explosions. The shattered condition of the concrete indicated that the stopping could not again withstand as great pressure as had been applied to it, and release of pressure over the top was all that prevented its blowing out completely.

DEFLECTION OF OUTER FACE

There are insufficient points to permit plotting the deflection of the outer face against pressure; moreover, the damage caused by the falling roof throws some doubt on the values obtained in the third test. Those given in Table 5 were accurate as far as could be determined, but there was no proof that small disturbances had not occurred. The pressure in the second test was nearly as great as in the third test, and the stopping could not have been far from failure, despite the fact that there was little evidence thereof. Consequently, the records of the second test are more important.



HORIZONTAL CROSS SECTION OF STOPPING



DEFLECTION AND SET IN HORIZONTAL PLANE

FIGURE 19.—Movement of outer face of stopping 4

Curve	Measurement	Test	Pressure, lbs. per sq. in.
1	Deflection	1	42
2	do	2	98
3	Set	1	42
4	do	2	98

The deflection and set of the outer face are plotted in Figure 19, which is similar to Figure 14 in arrangement. Lines *1* and *2* are the deflections and lines *3* and *4* the sets for tests 1 and 2, respectively. The lines have been extrapolated to meet the boundaries of the graph, and it is evident that the two halves of the stopping did not act alike. Line *1* meets zero deflection about 4 inches from the south end of the concrete, which indicates that there may have been cantilever action at the south rib in the first test. On the other hand, the north end of the concrete apparently was thrust forward bodily about 0.02 inch. The recorded permanent set (line *3*) after the test is difficult to interpret. The south half was apparently bent inward at its center, but this does not seem possible and may be due to an error in the measurements. The north end of the concrete apparently returned to about the position it had before the test.

In test 2, both ends of the concrete were thrust forward (line *2*), and there was evidently no cantilever action. Line *4* shows that part of this thrust was permanent. The north half of line *4* is straight, but the south half is bent similar to line *2*; no explanation can be offered. It will be noted that the north half of the stopping was bowed out in test 2 (line *2*), but this was not true of the south half.

DEFLECTION OF ENDS

The records obtained from the devices attached to the bars set in the end of the concrete are given in Table 5. Those for test 1 are irregular and not to be interpreted, but better results were obtained in the second test. The deflection and set, measured 11 inches from the outer face, were greater than similar movements recorded 1 inch from the face, indicating that there was rotational movement. Figure 19 shows that the centers of rotation of the halves were not far from the corners of the outer face and the ends of the concrete. If rotation is taken about these axes, the movement can be analyzed, and it is found that the south and north ends moved 0.112 and 0.099 inch parallel to the length of the stopping, respectively, under the maximum pressure. The readings indicate no permanent rotational set at the south end and evidently do not present a true record. The set parallel to the face could not have exceeded 0.043 inch, the record given by both devices there. At the north end the set parallel to the face was 0.039 inch. The total increase in length of the outer face of the stopping in test 2 was, then, 0.211 inch when under pressure and not over 0.072 inch when the pressure was removed. These values are, respectively, 0.2 and 0.07 per cent of the original length.

The deflection due to rotation corresponds to angular movement of 10 and 18 minutes of arc at the south and north ribs, respectively. The fact that the north half of the stopping was bowed and the south was not would cause a difference of this kind, but the magnitude is greater than would be expected. Probably there are errors in measurement or in the assumption concerning the location of the axes of rotation.

OTHER RECORDS

Width of vertical tension crack.—The devices on either side of the central tension crack operated satisfactorily in the first test only. The maximum deflection was 0.031 inch on the south side and 0.033 inch on the north side of the crack, a total opening of 0.064 inch. The permanent set was not divided so equally, however; there was 0.021 inch on the south and 0.009 inch on the north, a total of 0.030 inch. In test 2 no records were obtained on the south side of the crack, and on the north side the deflection and set were both 0.046

inch. This appears less unreasonable when it is remembered that the stopping was strained nearly to the breaking point.

Depth of tension crack.—The records of the wire and glass inserts were unsatisfactory. Evidently the wires were not properly bonded to the concrete, and they ruptured irregularly. The glass tubes containing acid were tested 3 days after the concrete had been poured and found in good condition; but 27 days later, when the tests were begun, no current could be passed through them. The acid probably crept up the tubes and attacked the copper wires. The records obtained from the tubes containing mercury were also irregular.

Compression of inner face.—The pins placed in the inner face were 19.25 inches apart and spaced equally on either side of the vertical center line. The concrete was compressed permanently in this distance 0.0046 inch after the first test. Measured from the original position of the pins the compression was 0.0187 and 0.0319 inch after the second and third tests, respectively. The pressure in test 2 was two and three-tenths times that in test 1, but the compression was four and one-tenth times as great. It may be that incipient crushing was present in the second test, but there was no visible evidence thereof. The compression in the second test was 0.097 per cent, but it was certainly not uniform over the measured distance. It was probably very small outside the pins and negligible in the outer quarters of the stopping.

CONCLUSIONS FOR STOPPING 4

This stopping gave the first definite evidence in the Experimental mine of the strength to be expected from the form of construction used when cantilever action was absent. The breaking pressure was twice that demanded by the operating regulations, and at least ten times as great as would be predicted for a similar slab freely supported. Comparison with stopping 3 showed that considerable additional strength was obtained when the ends were recessed deeply. The condition of the stopping after the third test proved conclusively that arch action was present, and the concrete at the center of the arch had to be crushed before the stopping failed. As far as could be seen or determined at the time there was no restraint at the floor or roof, but later results made it appear that this was not wholly true. Such restraint as was present did not place sufficient tension strain on the outer face to open additional tension cracks therein; it could have been found only by placing deflection-measuring instruments near the top and bottom and determining the difference in deflection between those points and the center.

STOPPING 5

CONSTRUCTION

The ratio of thickness to span of stopping 5 was about half that of stopping 4. This was accomplished by keeping the same thickness (12 inches) and doubling the span. It was necessary to enlarge the chamber considerably and the stopping was placed farther from the rear wall. Figure 20 is a plan of the chamber as prepared for tests of stopping 5. All the excavating was done at the south rib and the walls were sloped as required. The changes can be noted by comparison with Figure 8.

The finished stopping had a clear span of 15 feet 7 inches and a height of 7 feet 5 inches. With a thickness of 12 inches the ratio of thickness to span was 1 to 15.6. The depth of the recesses was 12 inches; this dimension was doubled to keep its ratio to span about the same as for stopping 4. The stopping was placed on a concrete base like the one preceding it, and precautions were taken to prevent bonding between the base and the concrete of the stopping. The concrete was carried to the roof, and the pins for measurement of shrinkage were set in the inner face. Shrinkage was complete at the end of 10 days. It amounted to 0.0010 inch in 19 inches, or 0.0053 per cent, and was equivalent to 0.011 inch in the total length of the concrete.

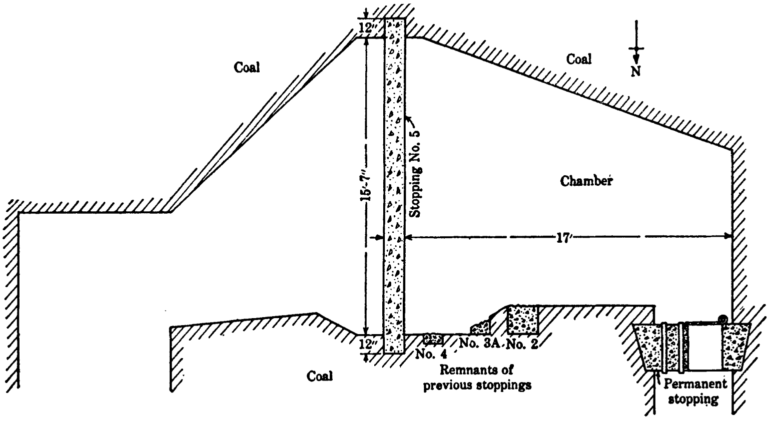


FIGURE 20.—Chamber prepared for tests of stopping 5

DEFLECTION MEASUREMENTS

Deflection of the outer face was measured at five points having the same relative position as in the tests of stopping 4; the actual spacing was greater because of the increased span. As previously, there were two devices to measure the movement on either side of the tension crack, but light angle irons were used instead of pins as inserts to give greater rigidity. Angle irons were also substituted for flat bars at the ends of the stopping, whose movement was measured as before. Figure 21 shows the arrangement at the north rib, which was duplicated at the south rib. Rods attached to the angle iron 1 and 11 inches from the outer face actuated deflection recorders. The outer recorder was arranged to give a time record of deflection.

Three sets of inserts were placed to record the depth of the tension crack. Carbon rods were used as the conductors; these were fixed in

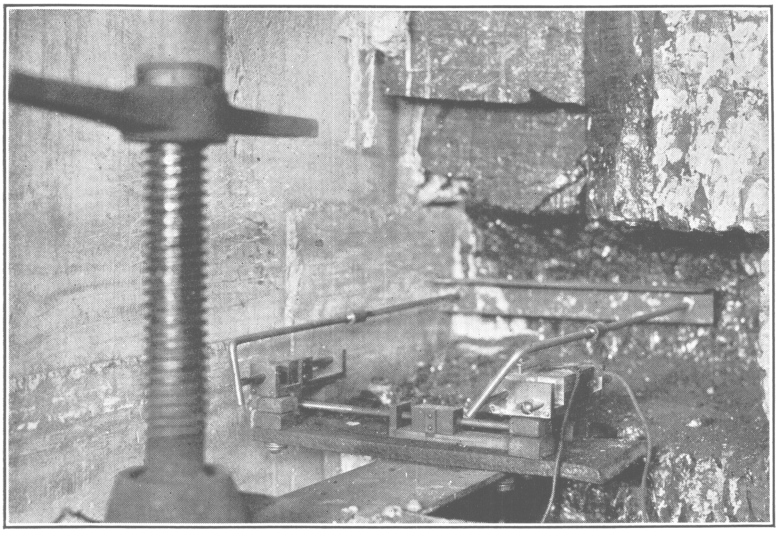


FIGURE 21.—Device for measuring end movement at north rib, stopping 5

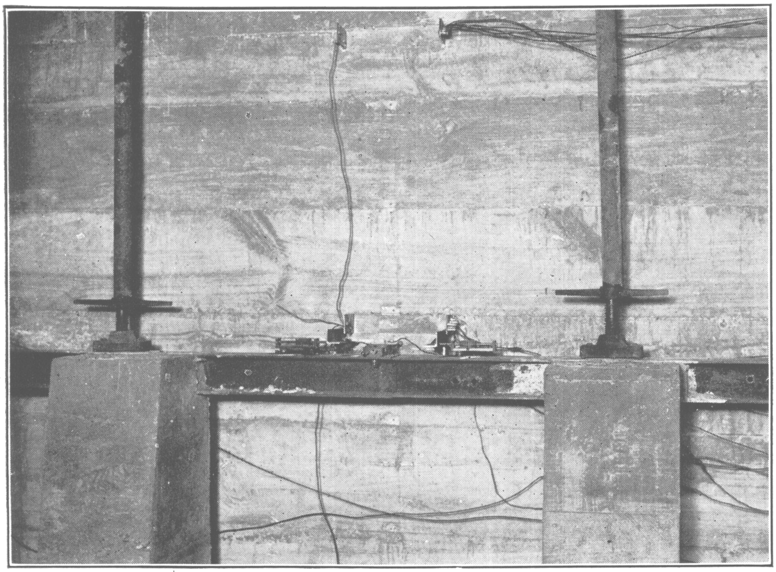


FIGURE 22.—Inserts and deflection-measuring devices at center of stopping 5

frames at 2-inch intervals, and the current was conducted to them by wires suitably insulated and soldered to one end of the rods, which were copper-plated. A common return wire connected all the opposite ends. The frames supported the wires, and the whole assembly was dipped in melted sealing wax to provide thorough insulation. The upper and lower inserts were about 1 foot from the roof and floor, respectively, and the center insert was just above the line of the deflection pins. Figure 22 is a photograph of the central portion of the stopping; the projecting ends of the top and center inserts can be seen, together with the central deflection recorder and recorders on either side of the vertical tension crack. The H-beam supporting the instruments was placed in two sections, each supported by two piers.

RESULTS OF TESTS

Tests of stopping 5 were begun on December 4, 1929. There were six tests, and the recording instruments operated satisfactorily in four of them. In the fifth, gas blew under the stopping and disturbed one of the piers, thus rendering the readings valueless. The stopping blew out completely in the sixth test. The primary data of the first four tests appear in Table 6.

TABLE 6.—*Results of tests of stopping 5*[1]

Condition	Test			
	1	2	3	4
Pressure lbs. per sq. in.	17.5	26.5	35.5	41
Deflection of center inch	.073	.186	.335	.528
Set of center do	.034	.096	.174	.270
Deflection of bar in south end, 1 inch from stopping do	.000	.005	.013	.013
Deflection of bar in south end, 11 inches from stopping do	.000	.004	.018	.028
Deflection of bar in north end, 1 inch from stopping do	.017	.017	.033	.045
Deflection of bar in north end, 11 inches from stopping do	.015	.039	.068	.087
Set of bar in south end, 1 inch from stopping do	.000	.000	.003	--------
Set of bar in south end, 11 inches from stopping do	.000	.006	.009	--------
Set of bar in north end, 1 inch from stopping do	.000	.007	.017	.017
Set of bar in north end, 11 inches from stopping do	.007	.021	.033	.040
Maximum width of central tension crack do	.010	.021	.029	.030
Final width of central tension crack do	.006	.014	.015	--------
Compression of inner face in 19 inches do	.001	.000	.003	.004

[1] All deflection measurements taken from position before first test.

VISUAL OBSERVATIONS

The vertical tension crack at the center opened slightly in the first test, but there was no other evidence of stress. This crack opened farther in the second test, and secondary fine tension cracks spread from it toward the lower corners of the stopping. All the cracks opened farther in the third test, and the secondary ones were extended. They were opened farther in the fourth test and a new one appeared in the north half. The location and extent of these cracks appear in Figure 23. The secondary cracks showed that the stopping was restrained at the bottom as well as at the ends. The pressure in test 5 was 55 pounds, and all these cracks were widened but not extended.

Tests 4 and 5 also caused cracks in the inner face, which are shown in Figure 24. These cracks offer confirming evidence of the fact that there was restraint at the floor; they also indicate that there was restraint at the roof to a minor extent. Two pieces spalled near the roof in test 5, as shown in Figure 24, indicating that the crushing strength of the concrete was exceeded. The smaller spalled area is approximately at the center, where crushing would be expected first, but the larger area to the right (south) in Figure 24 would not have been present had there been no restraint at the top. It indicates that top restraint was present principally in the north half of the stopping, which is confirmed by the fact that the irregular roughly vertical crack at the north rib was farther from it than the similar crack near the opposite end was from the south rib. Probably, however, crushing occurred to greater depth at the center, as a hole 1¼ inches in diameter was blown completely through the concrete near the roof. (See fig. 24.)

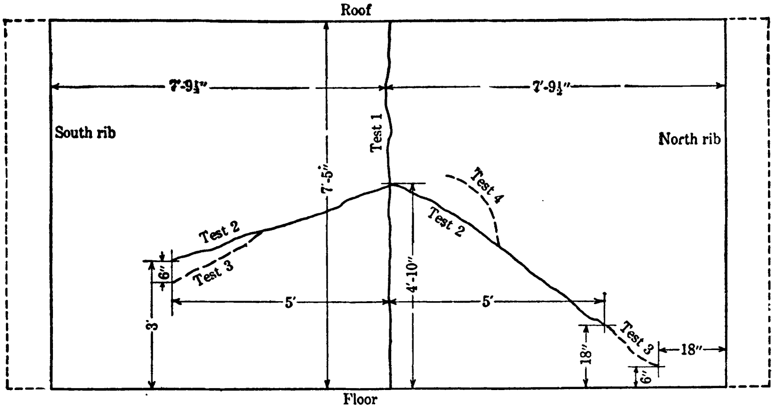


FIGURE 23.—Cracks in outer face of stopping 5 formed during first four tests

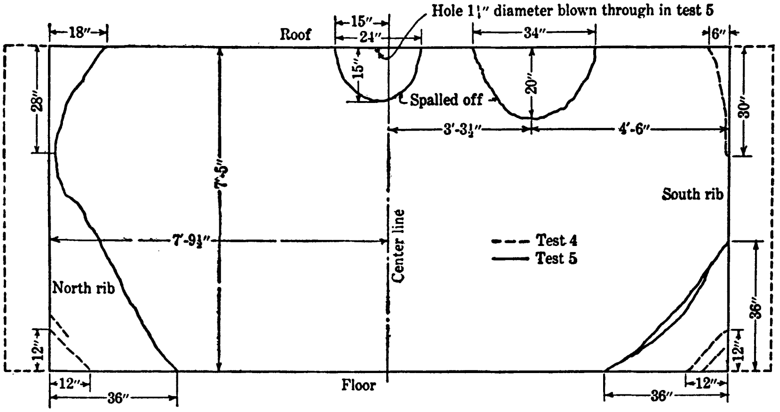
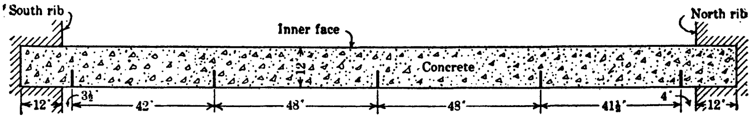


FIGURE 24.—Cracks in inner face of stopping 5 formed during tests 4 and 5

It appeared probable that the strength of this stopping had been exceeded in test 5, and one more test was made to confirm the matter after the junction of inner face and the roof was plastered to prevent leakage. The maximum pressure was 45 pounds (10 pounds less than in test 5), and the stopping blew out completely. Large pieces of concrete were left projecting from both ribs; their ends were determined by the outermost cracks shown in Figure 24. The concrete was broken into pieces ranging in weight from a few pounds to possibly a ton. These fragments were thrown to the opposite rib, and some were found several feet around the corner toward No. 1 right entry.

DEFLECTION OF OUTER FACE

There can be no doubt that deflection of the outer face was modified by the restraint at the bottom and top of the stopping. Had there been proper records the center would have been found to be bowed vertically as well as horizontally, and the absolute deflection of the center was less than would have been the case had there been end restraint only. The results have value, however, for comparison with those on stopping 6, which was similar in construction but restrained only at the ends. It is unfortunate that disturbance of the apparatus caused loss of the records in test 5, as that test determined the strength of the stopping; it is necessary, then, to consider principally tests 3 and 4. Tests 1 and 2 can be omitted because pressures therein were lower.



HORIZONTAL CROSS SECTION OF STOPPING

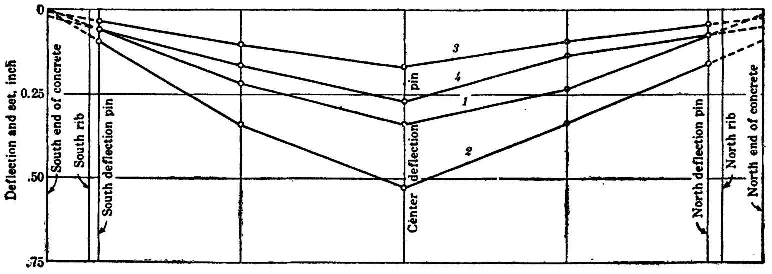


FIGURE 25.—Movement of outer face of stopping 5

Curve	Measurement	Test	Pressure, lbs. per sq. in.
1	Deflection	3	35.5
2	do	4	41
3	Set	3	35.5
4	do	4	41

The deflection and set recorded by the five pins along the horizontal center line in tests 3 and 4 of stopping 5 are plotted in Figure 25, which is similar to Figures 14 and 19. Lines *1* and *2* are the deflection and lines *3* and *4* the set in the respective tests. Extrapolation of the two deflection lines to the south rib causes them to intersect very close to the end of the concrete and zero deflection. This indicates practically no forward thrust of the end and no cantilever action. The line of set in test 3 meets this intersection when extrapolated but that of test 4 does not; it indicates a forward thrust, and this is believed to be an error in the records. It is noticeable that the south half was bowed in both tests, which agrees with the crushing of the inner face that took place at the roof near the center of the south half in test 5. (See fig. 24.) Deflection records for that test doubtless would have shown a sharper angle in the line.

Conditions were different in the north half of the stopping; the end was thrust forward slightly in test 3 and considerably in test 4. Also, there was no marked bowing of the concrete in the latter test and no crushing of the concrete in test 5. The lines of set indicate that the end did not return to its original position after test 4 but was thrust forward permanently. The result in test 3 is not consistent with the deflection. It is also believed that the record of set obtained at the pin midway between the center and north rib in test 4 is in error, because it is highly improbable that the concrete would be bent in a reverse direction, as the line in Figure 25 indicates.

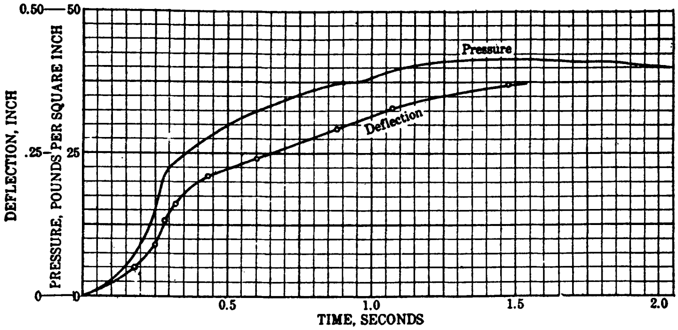


FIGURE 26.—Relation of development of pressure and deflection of center of span, test 4, of stopping 5

The deflection recorder at the center was arranged to give a time record, and the relation thereof to the development of pressure is important. The record for test 4 appears in Figure 26, where it is seen that deflection started simultaneously with pressure. Variations in the rate thereof were similar to variations in the rate of rise of pressure, and the maximum deflection occurred with maximum pressure. This record confirms results obtained at the Bureau of Standards.

DEFLECTION OF ENDS

The values given in Table 6 show that in all the tests, end deflection was considerably greater at the north than at the south rib, but the movement was sufficient to justify analysis only in test 4. Assuming that the axis of rotation was at the end of the outer face of the concrete, it is found that in this test direct end thrust under pressure amounted to 0.0115 inch at the south rib and 0.0408 inch at the north rib, a very large relative difference, which points to different behavior of the coal at the two points. Computation of the rotation of the two ends gives 5 minutes of arc for the south end and 14 minutes for the north end. Here, again, is a difference which is difficult to reconcile with the other records. If the two slabs remained perfectly flat and were independent, there would have to be a difference in forward thrust on the two sides of the vertical tension crack, a condition that could not escape notice, even if it was much smaller than these figures demanded. The two slabs were not independent, however; they were continuous beyond the end of the tension crack, and differential movement of the outer face could be obtained only by supposing an additional tension crack somewhere in the concrete parallel to the faces. There was no evidence that such a crack existed or any reason why it should exist. Again, the deflection records of the outer face (line *2*, fig. 25) indicated that the south half was bowed but the north was not, which should result in a greater angular movement at the south end, the reverse of what was found. It must be concluded that the method of determining angular deflection was not sufficiently accurate for the small movements that occurred. As direct end thrust was by far the larger part of the movement, determination thereof probably was subject to a smaller percentage error and is more reliable.

CONCLUSIONS FOR STOPPING 5

This stopping could not be compared direct with those preceding it because of the restraint at the floor and roof. Probably this restraint was due to wedging or irregularities of the roof and concrete base. The breaking strength was greater than would have been obtained if there had been restraint at the ends only, a fact proved by the tests of stopping 6.

STOPPING 6

CONSTRUCTION

In the construction of stopping 6 it was of primary importance to avoid restraint at the roof and floor. Restraint might come from bonding, friction, or wedging; avoidance of these required smooth parallel surfaces below and above the concrete coated with grease or other material repellant to wet cement. The concrete base was prepared as before and capped with a steel plate whose width was about twice the thickness of the stopping. This plate was anchored to the floor by bolts and the stopping was placed on it. The concrete was carried up to within 6 inches of the roof and allowed to set. After the form had been removed it was capped with mortar and a second plate was laid on it. The space over the plate was filled with concrete and the job finished with a cement gun. The upper plate also was anchored to the roof by bolts driven into stiff grout in holes bored to receive them.

The test chamber was so enlarged by this time that difficulty was experienced in finding a suitable place, without excessive length, for the stopping. It was placed 6 feet from the rear wall of the chamber, as Figure 27 shows. The relation to the outer entrance passageway can be seen by comparing this sketch with Figure 20. The stopping had a height of 6 feet 10 inches between plates, a clear span of 12 feet 8 inches, and a thickness of 9.5 inches; the ratio of thickness to span was then 1 to 16, practically the same as for stopping 5. The ends were recessed 6 inches, one-half as much as for stopping 5. However, the two stoppings were essentially duplicates, except for the absence of restraint at the roof and floor in stopping 6.

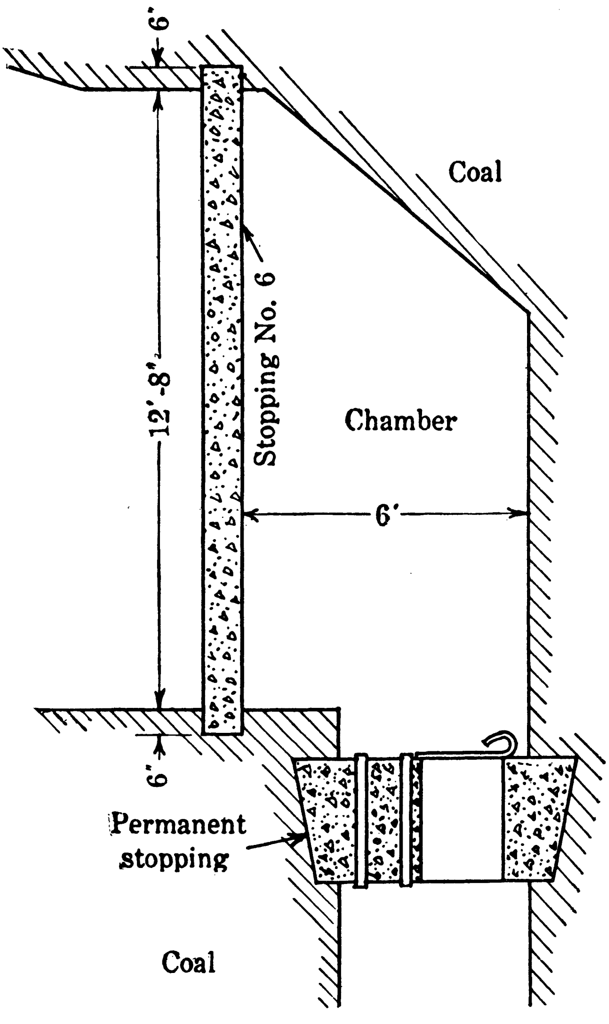


Figure 27.—Chamber prepared for tests of stopping 6

Pins for the measurement of shrinkage were set in the inner face, as before. Shrinkage continued for about 3 weeks and totaled 0.0022 inch in 19 inches, or 0.0106 per cent, and was equivalent to 0.019 inch in the length of the concrete.

DEFLECTION MEASUREMENTS

Deflection of the outer face was measured at five points, as with stopping 5. The devices at the central three points gave time records. Additional devices giving time records were placed near the roof and floor on the vertical center line. The double indicators for end movement were abandoned, single indicators only being used. The movement was obtained by the use of flat bars bent in the shape of a structural-iron **Z** bar. One leg of the **Z** was imbedded in the concrete at the end, the web of the **Z** lying between the outer face of the stopping and the coal wall of the recess, and the second leg was free just outside the coal rib. The device was arranged to indicate the movement of this leg. Figure 29 is a photograph of the stopping before the test and shows the various deflection recorders.

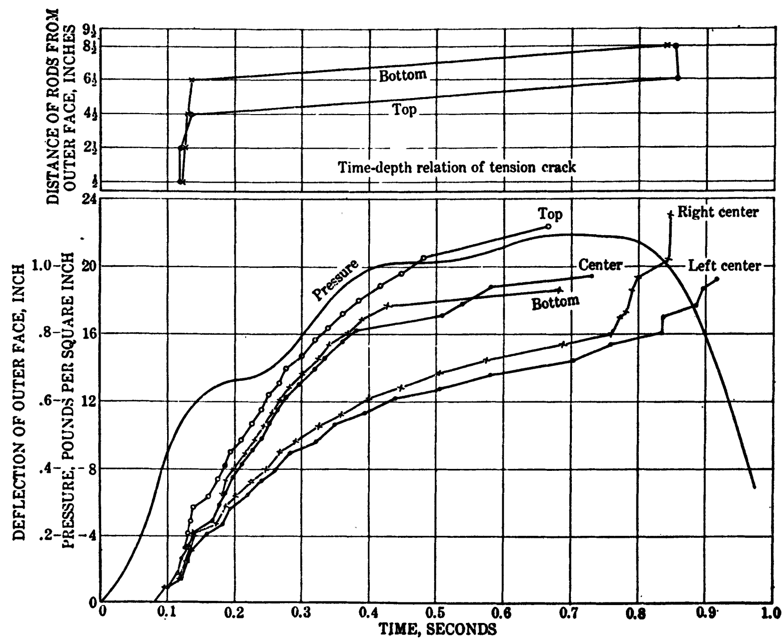


FIGURE 28.—Pressure and deflection records, test 1, of stopping 6

The width of the central tension crack was measured by a single device instead of two, as previously. This device was mounted on an angle iron imbedded in the concrete on one side of the crack, and the sliding rod was actuated by a similar angle imbedded on the opposite side. Steel rods were set in the concrete near the outer face and on either side of the tension crack about 20 inches from the roof and floor, with their adjacent ends exposed. Measurement of the increase in distance between the exposed ends was designed to give the final width of the crack at points in the concrete. This system was arranged so that the strength of the stopping would not be affected.

Carbon-rod inserts to measure the depth of the tension crack were placed 15 inches from the roof and floor and arranged as for stopping 5, except that completely separate electric circuits were provided for each rod. There were five rods in each set at 2-inch intervals, and the first was one-half inch from the outer face of the stopping. The ends of frames carrying these inserts, with wires leading from them, can be seen in Figure 29.

RESULTS OF TESTS

The stopping was tested on February 24, 1930. The first test developed a pressure of 22 pounds, and the stopping failed. Observers at the pit mouth heard a rumbling noise, followed by concussions such as would be produced by the fall of heavy objects. Examination showed that the concrete had crushed at the center of the inner face, and the two slabs had broken off at the ribs and fallen forward. Figure 30 is a photograph of the slabs taken from the same point as Figure 29. The original inner faces are exposed, and the front edges were originally at the center. Crushing and spalling of the inner face are evident.

The piers which supported the H-beam are seen in the picture, the right pier in the right foreground and the left pier under the left slab. The H-beam was bent and thrown to the entrance passageway. The steel plates at the roof and floor remained in place, the one at the roof is visible, and the upper corner of the right slab is resting against it and the concrete above it. It is evident from the picture that the left slab fell first and the right was thrown over it.

The only deflection records obtained were from the devices arranged to give a time record. These were the three on the vertical center line—top, center, and bottom—and one 32 inches horizontally on either side of the center, designated left center and right center, respectively. The records are plotted in Figure 28, together with those obtained from the carbon-rod inserts. The deflection curves are seen to have the same general shape as the pressure curve. The center and bottom deflected about equally, but deflection at the top was greater. These devices reached the limit of recordable travel at the last points shown. Those at left and right center gave similar records, but the absolute deflection was, of course, less than at the center. This fact had an interesting result, as the devices then recorded additional movement when the stopping failed. The maximum pressure was reached at 0.7 second, and shortly afterward both these devices recorded sharp increases in the rate of deflection; the change in the right-center record is particularly marked. Simultaneously, a rapid fall in the pressure began, indicating failure of the stopping.

The records of the carbon-rod inserts coincided with the other phenomena. The crack opened with extreme rapidity both at top and bottom. The time relation to the deflection records is believed to be exact, but it appears that both are delayed slightly with reference to the pressure record. There may be an error of synchronization. The recorded depth of the crack was 4½ inches at the top and 6½ inches at the bottom. There probably was not as great a difference as this indicates, because there is no way of telling how far beyond the 4½-inch rod the crack extended at the top. Again, one would expect a greater depth of crack at the top to correspond to the greater deflection recorded. The depth of crack apparently remained unchanged while the maximum pressure was developing, and the unbroken rods finally were ruptured when the stopping failed.

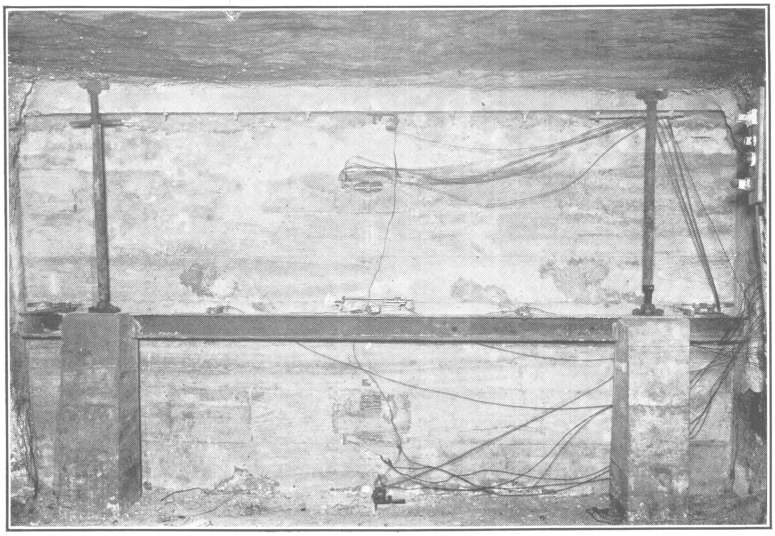


FIGURE 29.—Stopping 6 prior to test

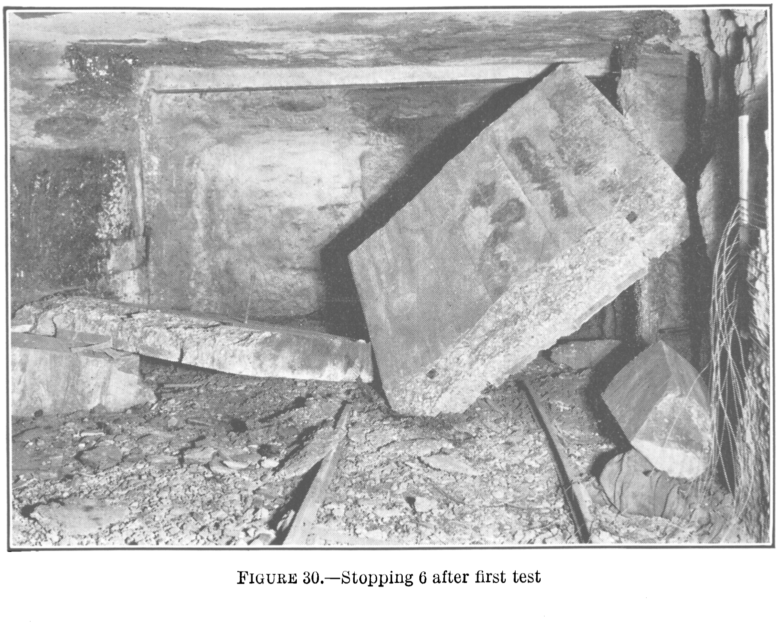


FIGURE 30.—Stopping 6 after first test

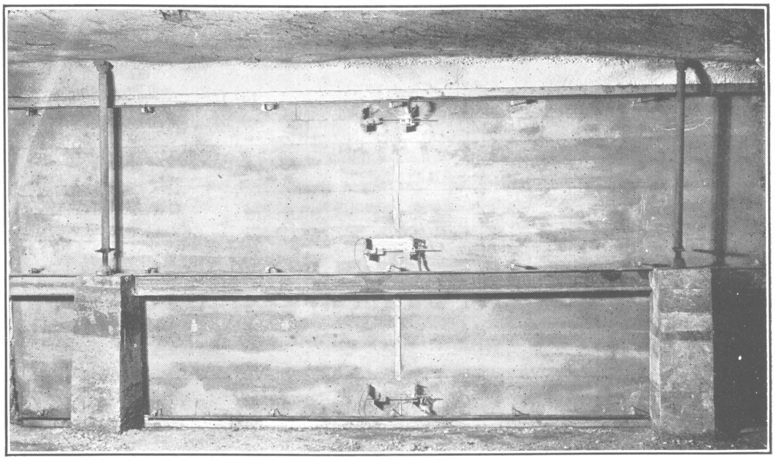


FIGURE 31.—Stopping 7 prior to test

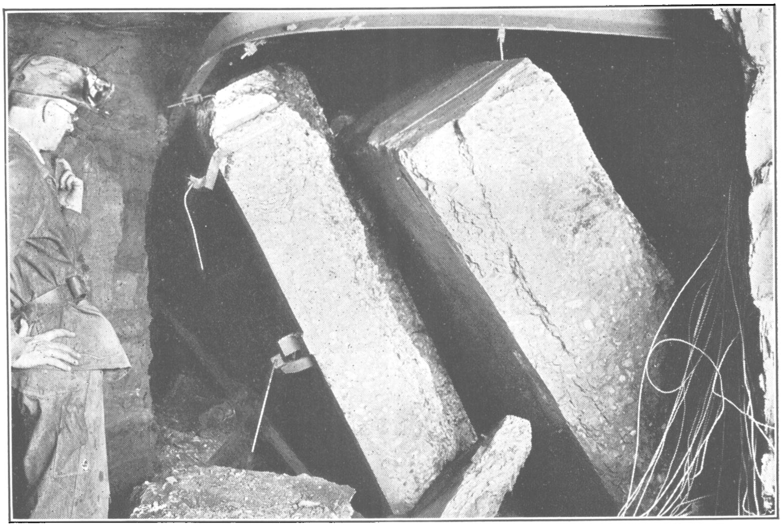


FIGURE 32.—Débris of stopping 7, viewed from corner of entrance passageway

Failure of this stopping at such a low pressure was surprising at the time, and it was thought that there might be an error somewhere to which it could be attributed. Analysis of the data from all the stoppings indicated the contrary and pointed to unrecognized restraint at roof and floor in stoppings before stopping 5, as is shown later. The importance of this factor is realized when stoppings 5 and 6 are compared. Structurally both were similar; the only difference lay in the restraint at top and bottom in stopping 5, yet this was sufficient to give it a strength two and a half times that of stopping 6. This is a single result, and it was not safe to draw general conclusions from it except in a qualitative manner.

CONCLUSIONS FOR STOPPING 6

The single test of this stopping emphasized the necessity of avoiding restraint at roof and floor if consistent and understandable results were to be obtained. It further confirmed the fact that applied pressure and resultant deflection were similar in rate and duration, consequently time measurements were not necessary with the next stopping.

STOPPING 7

DESIGN AND CONSTRUCTION

The design of stopping 7 was based upon an analysis of all previous test results by D. E. Parsons. A tentative relation between ratio of thickness to span and breaking strength was developed, which assumed that the strength varied as the square of the ratio. Stoppings 3 to 5 showed greater strength than would be predicted, which could certainly be ascribed to restraint of top and bottom in stopping 5. Similar action, but less marked, might be assumed for the others. The highest pressure applied to stopping 2 was much less than its indicated strength. It also appeared that a stopping having a ratio of thickness to span of 1 to 10 should fail at a pressure of 55 pounds, which was close to the demand of the operating regulations, and stopping 7 was prepared in accordance with this ratio.

Stopping 7 was placed 9.5 feet from the rear wall of the chamber, practically at the location of stopping 2. The north rib was excavated to remove the imbedded concrete of stopping 2 and expose fresh coal. The coal along this rib had been exposed to all the tests made and apparently was affected by the heat of the explosions. There was surface evidence of this, and compressibility tests described in a later section proved the point, as the exposed coal had much greater compressibility and permanent set on removal of pressure than did fresh coal at the opposite rib. Because of the excavation required to prepare both ribs the minimum span obtainable was 16 feet 3 inches, and the thickness then had to be 19.5 inches to get the desired ratio. The recesses were 7.7 inches deep; their ratio to span was the same as in stopping 6. The height of the stopping was 6 feet 10 inches, and steel plates were used above and below it as before. This stopping had the greatest length and thickness of any tested, and the volume of concrete in it was 7.21 cubic yards. Shrinkage was greater and continued over a longer period than with any of the preceding stoppings. It amounted to 0.0050 inch in 18.25 inches, or

0.0044 per cent, which is equivalent to a reduction of 0.058 inch in the total length of the concrete.

DEFLECTION MEASUREMENTS

Deflection of the outer face was measured at points on the horizontal center line as before and near the top and bottom in addition. There were seven points of measurement spaced equally along each line, as may be seen in Figure 31, a photograph taken before the first test. The central row of devices was supported by piers and an H-beam as before; those near the roof and floor were fastened to Z-bars held in place by the bolts, which secured the upper and lower steel plates to the roof and floors.

Devices for measuring the width of the tension crack were placed near the top, center, and bottom, and carbon-rod inserts were placed just above them. These rods were 4, 8, 12, 14, 16, and 18 inches from the outer face at each level. This spacing was adopted to put a larger number of rods toward the rear of the stopping, where compression would occur.

Measurement of the movement of the ends was omitted in tests of stopping 7.

An attempt was made to obtain more detailed information on compression of the inner face. Pins were inserted 9 and 27 inches on either side of the center line near the top, center, and bottom. There were then at each level three 18-inch spaces, with the central one bisected by the vertical center line of the face. The change in distance between the pins was measured after each test with an inside micrometer caliper.

RESULTS OF TESTS

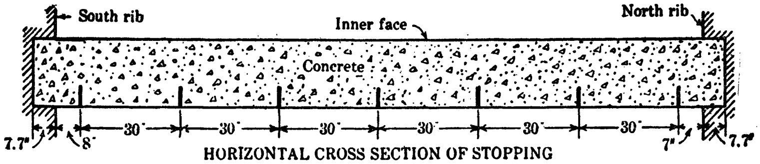
Tests of stopping 7 were begun on July 10, 1930. There were four tests; in the last the stopping blew out at a pressure of 55 pounds. Excellent deflection records were obtained in the first three, in which the pressures were 20, 36, and 50 pounds. The number of records was so large that a simple presentation in tabular form is impossible.

VISUAL OBSERVATIONS

The only sign of stress observed in the first test was the vertical tension crack in the center; this was widened in the second test, and there were signs of tension at the junctions of the inner face and the ribs. The third test enlarged the tension crack farther, and a second fine tension crack appeared 2 feet to the right (north) and parallel to it. There were signs of incipient failure due to crushing of the inner face at the center. Irregular cracks were present, outlining pieces that would spall on further compression. The pressure (50 pounds) was not far from that required to break the stopping.

Observers at the pit mouth heard a sharp report and observed a flurry of dust when the fourth test was made. Inspection showed that the portion of the stopping between the primary and secondary tension cracks had been broken into a number of pieces; the remaining slabs had broken off at the ribs and had been thrown outby about 10 feet against the rib without overturning. The fragments of the central portion were scattered under and outby the slabs with the remains of the piers and recording instruments. The slab at the south rib had moved first and turned through an angle of 45° as it moved.

The north slab had turned through 135° and was leaning against the first slab; the inner surfaces of the two slabs were together. As they stood nearly vertical they practically blocked the passageway at the corner. Figure 32 is a view of the ends of the slabs as seen on entering the outer passageway leading to the chamber. The visible ends of the slabs were originally at the center of the stopping. The left slab is from the south rib; it will be noticed that it appears thinner than the other, due to spalling of the inner face as the stopping broke. The spalled portion is somewhat shaded. The end of the north half was determined by the secondary tension crack, and the spalled portion of this half had been broken into fragments.



HORIZONTAL CROSS SECTION OF STOPPING

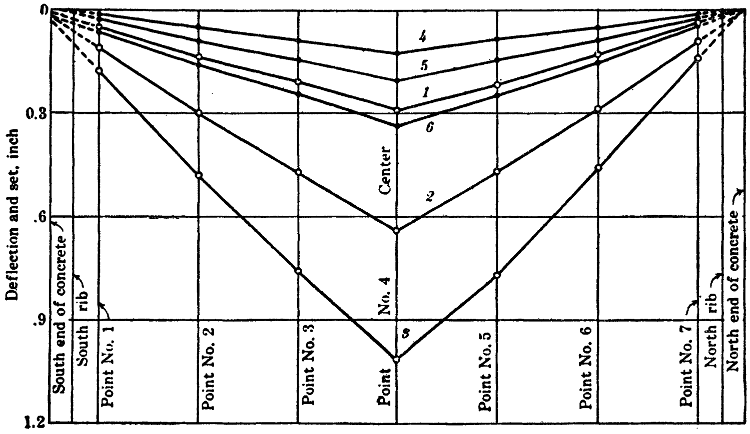


FIGURE 33.—Movement of outer face of stopping 7

Curve	Measurement	Test	Pressure, lbs. per sq. in.
1	Deflection	1	20
2	do	2	36
3	do	3	50
4	Set	1	20
5	do	2	36
6	do	3	50

Figure 35 (p. 58) is a view of the two slabs from their original position. The north slab is on top, and the visible face thereof was originally part of the outer face of the stopping. The exposed ends of both slabs are from the ribs. It will be observed that the junction of the outer face and rib end of the north half spalled, showing that there was strong compression at that point when the slab broke.

DEFLECTION OF OUTER FACE

The values of deflection and set obtained from the seven points along the horizontal center line are plotted in Figure 33. Curves

1, *2*, and *3* are deflection records for the first three tests. The number of points is sufficient to permit drawing curves instead of straight lines, and it is seen that each half of the stopping was bowed in each test, slightly in test 1 and markedly in test 3. The curve for the north half in test 3 has a break at the place of the secondary tension crack. It is seen that the curve fitting points 7, 6, and 5 would fall beyond point 4 if continued without a sharper curvature of some kind, and a break at the secondary tension crack is certain. Extrapolation of the curves for the north half carries them all close to the end of the concrete, and it appears that the slab hinged there without cantilever action. The south half behaved somewhat differently; the end of the concrete was thrust forward by increasing amounts in successive tests. This precludes cantilever action.

Lines *4*, *5*, and *6* give the permanent set after the three tests. Lines *4* and *5* are straight, and line *6* is slightly bowed, indicating that the concrete in each half was strained beyond possibility of complete recovery. Extrapolation of these lines confirms the conclusions drawn from the curves of deflection.

The records obtained at the top and bottom of the stopping showed to what degree deflection was uniform along vertical lines. It is doubtful if much significance can be attached to small differences, because the errors of experiment can not be estimated properly. It seems best to attach particular significance to these differences only when they exceed 0.01 inch. On this basis there was not sufficient difference of movement in test 1 to warrant analysis.

In test 2 there was an indication that the horizontal center line of the south half was thrust out by the maximum pressure more than either top or bottom; that is, it was bowed vertically as well as horizontally. However, the differences were little more than the limiting value of 0.01 inch. The bottom of the north half was consistently thrust forward the most and the top the least; but the center was always in advance of a line joining top and bottom, indicating that there was a vertical bow in the concrete. The difference in movement of top and bottom was 0.04 inch at the north rib (vertical line through point 7), 0.05 inch at point 6, and 0.03 inch at point 5; this may indicate restraint at the roof.

In test 3 conditions in the south half differed from those of test 2, principally in degree. Movement at top and bottom was about the same, but the horizontal center line was thrust forward as much as 0.02 inch beyond these points. Movement along the vertical center line was practically uniform. In the north half the condition of greatest movement at the bottom was repeated, the differences ranging from 0.05 to 0.07 inch. The horizontal center line was everywhere in advance of a straight line joining top and bottom.

On turning to the records of permanent set it is seen that there were no systematic differences greater than 0.01 inch in the south half in any of the tests. Such differences as occurred indicated that the bottom was displaced slightly more than the top. The values for the north half were of the same kind as were obtained for deflection—the bottom was thrust forward most and the top least. The differences amounted to 0.03 to 0.04 inch in test 3.

Probably there was as little restraint at the top and bottom of this stopping as could be obtained in any full-scale construction. The fact that the stopping was bowed slightly in the vertical direction indicates that perfect freedom therefrom was not obtained, but what existed was certainly very much smaller than that which occurred when top and bottom plates were not used; that is, with the stoppings before 6.

DEPTH OF TENSION CRACK

The carbon-rod inserts gave an excellent record of the depth of the vertical tension crack at the center of the stopping. All the rods 14 inches from the outer face were broken in test 1 and the crack did not extend to the rods 16 inches deep either in test 2 or 3. The crack formed rapidly when started, reaching its maximum depth in less than 0.2 second. The pressure in test 1 was about 10 pounds when the crack started and about 16 pounds when it reached maximum depth. The thickness of the concrete in compression was between 3.5 and 5.5 inches. It seems likely that the smaller value was approached, at least in test 3. The records also showed that the crack closed to some extent when the pressure was released. The rods 10 and 12 inches from the outer face remade contact after test 1, as did the bottom rod 8 inches from the face. These contacts were broken again in test 2, and only the 14-inch rod at the top remade contact after this test. None of the rods remade contact after test 3; there were, then, circuits only through the unbroken rods at depths of 16 and 18 inches.

Incipient destruction of the stopping in test 4 caused all the 14-inch rods to remake contact after the maximum pressure was reached, which indicated that the concrete back of the crack was crushing, causing the crack to close up. Finally all the rods at depths of 14, 16, and 18 inches broke contact in a period of 0.01 second, and there was a simultaneous rapid fall of pressure, indicating failure of the stopping.

The noticeable point in these records is that the depth of the crack altered but little after it was first formed, which argues that the distribution of stress in the central portion of the stopping was fairly constant over a wide range of pressure.

OTHER RECORDS

Width of tension crack.—There was no systematic difference in the maximum width of the vertical tension crack, as measured at the top, center, and bottom of the stopping. The respective widths, measured at the center, were 0.102, 0.270, and 0.311 inch in the three tests. The corresponding angles between the faces of the crack are 18, 49, and 56 minutes. The outstanding point is the small increase between tests 2 and 3 for a considerable increase in pressure.

The final width of this crack was always greater at the center than at top or bottom, but the differences did not exceed 0.007 inch. The final respective widths at the center were 0.048, 0.079, and 0.112 inch in the three tests. These correspond to angles of 9, 14, and 20 minutes.

Compression of inner face.—Compression in the 18-inch span across the center of the inner face of the stopping was uniform at top, center, and bottom in all tests. The maximum recorded difference in the three readings in any test was 0.002 inch, little more than the error of measurement. Compression at the center was 0.007 inch in test 1, 0.011 inch in test 2, and 0.019 inch in test 3; these are equivalent to 0.04, 0.06, and 0.11 per cent, respectively. Compression over 18-inch spans on either side was much less; it was scarcely measurable in test 1 and was about 0.003 and 0.007 inch in tests 2 and 3, or, in round figures, one-fourth to one-third the compression across the center.

CONCLUSIONS FOR STOPPING 7

This stopping broke at the pressure predicted but was strained considerably by a pressure 5 pounds lower. The rule of design was confirmed satisfactorily, and a ratio of thickness to span of 1 to 10 was indicated for stoppings designed to meet the operating regulations, provided that an equal amount of end restraint or its equivalent was present. Further tests of concrete stoppings were considered unnecessary, as the elements of the problem were determined and could be made the subject of separate investigations if desirable.

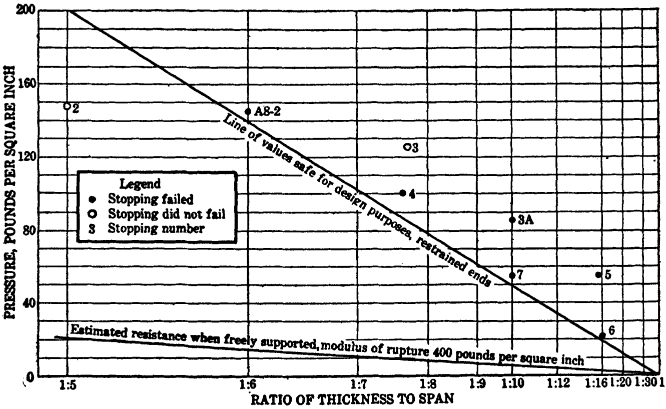


FIGURE 34.—Relation of strength of plain concrete stoppings tested to ratio of thickness to span

CORRELATION OF RESULTS

RELATION OF STRENGTH AND RATIO OF THICKNESS TO SPAN

The strength of the stoppings was a function of their ratio of thickness to span. The pressures that caused failures are plotted against this ratio in Figure 34, which gives the results obtained with stoppings 2 to 7, inclusive, and with slab A8–2 tested at the Bureau of Standards. The strength appears to vary directly as the square of the ratio of thickness to span, and the ratios have been plotted squared so that the relation will appear as a straight line. The upper diagonal line is drawn so that it reaches ratio 1: infinity—that is, zero—at zero strength; it has been passed just below the points for stoppings 6 and 7, as restraint at top and bottom was at a minimum with them. Extended upward to the left, it passes just below the result for slab A8–2.

Stoppings 3A and 5 had practically the same ratio of thickness to span as stoppings 7 and 6, respectively. The higher pressures required to cause failure of stoppings 3A and 5 were evidently due to restraint at top and bottom. It is also true that the full pressure probably was not effective over the entire span of stopping 3A, which would give a higher unit breaking load. No doubt there was restraint at the top and bottom of stoppings 3 and 4, but it could not have been discovered under the conditions of test until the stress caused by it in the outer face exceeded the tensile strength of the concrete, when tension cracks would appear similar to those that developed in stopping 5. Cantilever action was also present in stopping 3 because of the deep recesses in the coal.

There was no restraint at the top and bottom of slab A8–2, but the manometric record of the test showed that the pressure probably exceeded somewhat the minimum required for failure. In studying these results it must be remembered that the pressure required to cause failure was not determined with an accuracy much greater than 5 pounds. Thus, stopping 7 showed incipient failure at a pressure of 50 pounds, 5 pounds less than the failing pressure. The duration of pressure becomes important if accurate measurements are desired. A stopping may withstand a pressure several pounds greater than its failing strength easily if the duration is brief enough.

Finally, it will be noted that the maximum pressure applied to stopping 2 was much less than that estimated to produce failure. A pressure of at least 225 pounds probably would have been required if allowance is made for some restraint at top or bottom and for the cantilever action developed in the deep recesses used.

The lower diagonal line in Figure 34 gives the estimated resistance that similar plain concrete stoppings would have if they were supported but not restrained; that is, if they were simple beams. It is based on a modulus of rupture of 400 pounds per square inch. The strength is about one-tenth of that found when the ends are restrained and arch action is developed.

THICKNESS OF CONCRETE IN COMPRESSION AT CENTER

Failure of the stoppings was always due to crushing in a vertical zone at the center of the inner face, and the strength depended principally upon the thickness of concrete in compression at that point. If the depth of the tension crack was known accurately, the thickness in compression could be computed. Unfortunately the measurements permit determination of the limiting values only. Depth of the tension crack before failure was measured in tests of stopping 6 and 7 alone. The crack in stopping 6 had a depth greater than 6.5 inches and less than 8.5 inches. These figures are 68 and 90 per cent, respectively, of the total thickness of 9.5 inches. The crack in stopping 7 had a depth greater than 14 inches and less than 16 inches, values equivalent to 72 and 82 per cent of the total thickness, 19.5 inches. At the end of the crack the concrete was under tension stress very slightly less than its tensile strength. Because of the low ratio of tensile to compressive strength the neutral axis was close to the end of the crack; possibly 90 per cent of the unbroken concrete was in compression. By using the values from stopping 7, between 18 and 28 per cent of the concrete was unruptured; 90 per cent of these figures is 16 and 25 per cent, respectively. One can merely take an average and say that approximately 20 per cent of the concrete was in compression at the center. This figure may vary somewhat with the ratio of thickness to span, but no conclusion can be drawn from the limited data other than that the variation probably is not large.

DISTRIBUTION OF STRESS IN CONCRETE

If proper measurements could be made, one could outline a zone in any horizontal cross section of the stopping in which all the concrete would be in compression. This zone would be arch shaped and would correspond to the conception of a secondary arch used in one method of designing arch dams.[11] In a stopping such an arch would be tangent to the center of the inner face thereof, and its ends would be against the abutments. Its outer surface may be considered as passing through the junction of the abutments and the outer face of the stopping. If all the concrete outside this arch were removed, the strength under uniform loading would be reduced but slightly. Determination of the size and shape of this zone would be important in the general consideration of structures but has little practical significance for mine stoppings. The stopping must withstand pressure from either direction, and the area of the two opposing zones then required would cover most of the cross-sectional area of the stopping. Even if a stopping were to withstand pressure from one direction only the possible saving in volume of concrete obtained by omitting the excess outside the arch probably would be more than offset by the greater cost of constructing the forms of special shape that would be required.

The test results indicated clearly that compression stress first exceeded crushing strength at the center of the inner face. The concrete at the surface crushed first. The zone of crushing traveled inward until it reached the end of the tension crack formed in the opposite face, when the two halves of the stopping became independent of each other and were essentially cantilevers held by the ends recessed in the ribs. The plain concrete had little strength as a simple cantilever, and the halves immediately broke off at the rib line.

As previously noted, test 3 of stopping 7 showed incipient crushing of the center of the inner face clearly, cracks being present which outlined crushed areas. The stress had not been sufficient, however. to cause the crushed concrete to crumble and fall. Figure 18, relating to stopping 4, shows a later stage in crushing failure. Here a vertical zone has been crushed and broken out, and the fragments may be seen on the floor. The depth of the spalled area is not great—less than 1 inch maximum—but the concrete immediately under it is doubtless crushed to some extent. The final crushing, which caused release of

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[11] For example, see Jakobsen, B. F.: Approximate Formulas for Arch Dam Design: Engineering and Contracting, vol. 67, No. 1, January, 1928, pp. 25–27.

the two halves, is illustrated well by the left slab in Figure 30 and less clearly by the second slab in that picture and the left slab in Figure 32.

FORWARD THRUST AT ENDS OF CONCRETE

Extrapolation of the deflection curves to the ends of the concrete in the recesses indicated that one end of the concrete was usually thrust forward, compressing the coal on the outer face of the recess, while the other end was not. The total load on the stopping in any test could be computed from the pressure and the exposed area. As a first approximation one might assume that this was balanced by an equal and opposite total force supplied by the outer face of the recesses in the coal, against which the stopping was thrust, and the unit load thus put on the coal could be computed. Tests of the compressibility of the coal (described later) gave some idea of the compression which would accompany such loads. It was found, however, that the observed forward thrust was always considerably less than that computed from the compression-test data. Part of the discrepancy may have been due to differences in size and shape between the areas tested in compression and those which received the thrust of the stopping, but it is also evident that part of the load on the stopping was carried by the end faces of the concrete. When the concrete was poured it was spaded in the recesses thoroughly, and all the irregularities on the surface of the coal were filled. The concrete probably became more or less integral with the coal when it hardened, and movement of the end relative to the coal could occur only when shearing took place. The rotational movement of the halves also would tend to press the front corners into the coal, shearing would be accentuated there, and a frictional resistance would develop. Apparently the combined shearing and frictional resistance were important in resisting the forward thrust of the ends.

MAXIMUM ALLOWABLE SIZE OF STOPPING

The height of the stoppings tested ranged from 6 feet 10 inches to 7 feet 5 inches; the spans ranged from 7 feet 8 inches to 16 feet 3 inches. The relation shown in Figure 34 is established satisfactorily for any stopping whose dimensions are less than the maximum tested, but some provision must be made for greater heights and spans.

Consider first the effect of increasing the height of the stopping: With a given pressure the total load and total area increase in proportion, and the pressure per unit area and the stresses in the concrete remain the same, provided that both stoppings are exactly similar in all other respects. It is not certain, however, that this similarity will exist under mining conditions. In some mines in thick coal beds in the public-land States of the West there are places where the height of a passageway is greater than its width; in such places it will be safer to make the stoppings somewhat thicker than the specifications demand, particularly if any difference in bearing strength or compressibility of the coal bed at different elevations is suspected.

With regard to longer spans general knowledge of the behavior of structures gives some assurance that the designated ratio of thickness to span can be maintained. A span of 30 feet is considered allowable under the specifications formulated, but it is questionable whether greater lengths could be approved without experimental evidence of their strength. The thickness becomes large with long spans; thus the thickness would have to be 3 feet when the span was 30 feet. Such a stopping 7 feet high, recessed 3 feet in each rib and 6 inches in the floor, would contain 30 cubic yards of concrete. The handling of such a volume of material would be a serious problem in some instances. The thickness can be reduced if a buttress is provided at the center or if reinforcing is used. However, these are special cases not met under normal conditions of mining, and it is considered inadvisable to give general specifications to cover them; each case should be treated as a special problem when it arises.

SHRINKAGE OF CONCRETE

The shrinkage was measured between points 18 to 19 inches apart, expressed as a percentage of the measured distance and the equivalent reduction in the total length of the concrete computed. The values obtained are summarized in Table 7.

Table 7.—*Shrinkage of concrete, stoppings 2 to 7*

Stopping	Shrinkage	Reduction in length
	Per cent	*Inch*
2	0.010	0.013
3	.007	.009
4	.005	.005
5	0.005	0.011
6	.011	.019
7	.027	.058

The shrinkage of concrete is known to vary considerably with the moisture conditions under which it is cured; thus concrete aged under water expands instead of shrinking. Conditions at the stopping-test chamber varied little at different times and seasons. There was no direct circulation of air, the humidity was high, and the temperature was fairly constant. It may be inferred that conditions of aging were the same in all instances. Relative shrinkage must then have depended on other things, such as the consistency of the concrete, which is known to have an influence. No correlation can be made, however, as the consistency was not measured. It is a curious fact that the relative shrinkage of stoppings 2, 3, 4, and 7 was approximately related to the volume of concrete present, but stoppings 5 and 6 diverged from this relation considerably. Stopping 5 shrank less and stopping 6 more in proportion to their volume than did the others.

In so far as the strength of the stoppings is concerned the important point is the reduction in length of the concrete by shrinkage. If it is supposed that the ends of the concrete were originally in contact with the coal and shrinkage was uniform throughout the slab, gaps were formed at each end. When pressure was applied to the stopping these gaps would have to be closed before the ends were restrained. One can conceive, then, that the strength of the stopping might have been reduced; in fact, it was expectation of this result that led to attempted careful measurement of shrinkage. It will be noted that this hypothesis is opposed to the theory previously set forth concerning the absence or small value of forward thrust at the ends, namely, that the ends of the concrete were integral with the coal. The latter develops from the test results, whereas the former was a supposition before tests of stopping 2. Discussion of the relation of shrinkage to end movement follows.

END MOVEMENT PARALLEL TO FACES

The amount of movement of the ends parallel to the faces depended upon the ability of the coal to resist the load placed upon it. It was thus determined jointly by the load on the stopping and the compressibility of the coal; tests of the latter are described below. Records of end deflection were obtained for stoppings 3, 3A, 4, and 5. Those for 3 and 3A were a summation of the movement of the two ends; with stoppings 4 and 5 movement of the two ends was measured separately. Movement of the two ends of stopping 4 was approximately equal, but with stopping 5 the north end deflected over three times as much as the south end. This may be interpreted as a difference in compressibility of the coal at the two points, but the matter is complicated by the bottom restraint present. On the whole, it appears better to use the total movement of the two ends in considering the results. It may be repeated here that satisfactory measurements were obtained only in those tests in which the stopping approached failure. The data appear in Table 8.

TABLE 8.—*End movement of concrete, stoppings 3 to 5*

Stopping	Ratio, thickness to span		Pressure	Total end movement	Total shrinkage
	Proportion	Decimal			
			Lbs. per sq. in.	*Inch*	*Inch*
3	1:7.7	0.130	125	0.220	0.009
3A	1:10	.100	69	.279	.009
4	1:7.6	.132	98	.211	.005
5	1:15.6	.064	41	.053	.011

An attempt to relate the end movement and shrinkage to the pressure and ratio of thickness to span meets with failure. Conditions in the four cases differed; there was cantilever action in stopping 3, cutting away the recesses may have altered conditions for stopping 3A, and there was bottom restraint of stopping 5. Of equal or greater importance is the fact that the movement was a secondary phenomenon and determined by compressibility of the coal.

The only safe conclusion after a study of these results and of Figure 34 is that in no instance did shrinkage of the concrete result in appreciable weakening of the stopping. If such an effect were present, it should have been manifested in stopping 7, in which the computed reduction in length was 0.058 inch and greater than the total end movement of stopping 5. Despite this the result of tests of stopping 7 shows no irregularity in Figure 34. The agreement argues further that the total movement present in any one of the stoppings caused so little reduction in its strength that the difference between rigid abutments and those which yield like the Pittsburgh coal bed has no significance. This does not mean that similar results would be obtained in other coal beds; the strength and compactness of coals vary widely, and the Pittsburgh coal may be classed among the stronger beds. The present study would not be complete without some definite knowledge of the compressibility of the coal, as its ability to resist pressure as a buttress against the arching stress of a stopping determines the ultimate resistance of the stopping.

COMPRESSIBILITY OF PITTSBURGH COAL BED

Compressibility and bearing strength of the coal bed laterally were determined by means of a 60-ton hydraulic jack and steel cylinders spanning a passageway, so that pressure exerted by the jack was applied to both ribs through steel plates of known size. Details of the method are given in the appendix. Because of the limited capacity of the jack compressibility data could be obtained only with plates having an area of 144 square inches (12 inches square) or less. Most of the data were obtained with plates whose area was 34.46 square inches (5.87 inches square). Bearing strength could be obtained only with plates 2 inches square. The results obtained may be summarized as follows:

1. When pressure is applied laterally to a small area of a free face of the Pittsburgh coal bed that area is compressed, and it is probable that the coal immediately surrounding the area deflects similarly, but to a smaller degree. When the pressure is removed the coal recovers most of the compression, but there is always some permanent set. Additional cycles of compression and decompression cause only small increases in the set, and after the fourth cycle the compression is entirely elastic.
2. The compression obtained with a given load per unit area depends upon the size of the area loaded and increases as that area increases within the limits of the present work. The data obtained to date are not sufficient to determine the relation between compression and compressed area in a satisfactory manner.
3. Variation in compressibility at different elevations in the coal bed was not sufficient to be a factor when the strength of the coal as a buttress is considered.
4. Variation in compressibility between points 425 feet apart in the Experimental mine was not sufficient to affect the strength of a stopping buttressed against the coal. Although this is reassuring it does not preclude larger variations when much greater distances are considered in any given coal bed.
5. Compressibility was practically the same across the face and butt cleats—that is, in two directions at right angles to each other in a horizontal plane—and one would expect the same strength in stoppings placed in either of these directions.
6. A coal rib that had been disturbed was found to be much more compressible than one that was not disturbed. The test showing

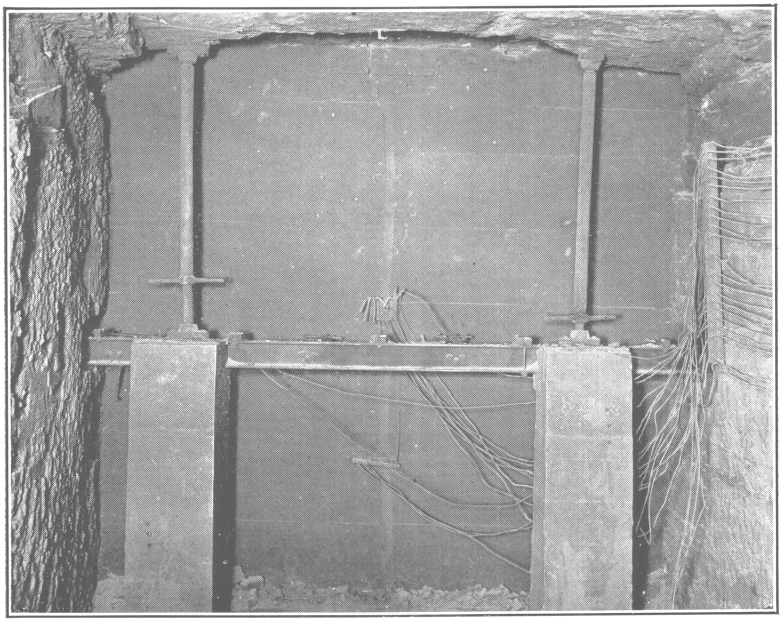

FIGURE 17.—Outer face of stopping 4 after third test

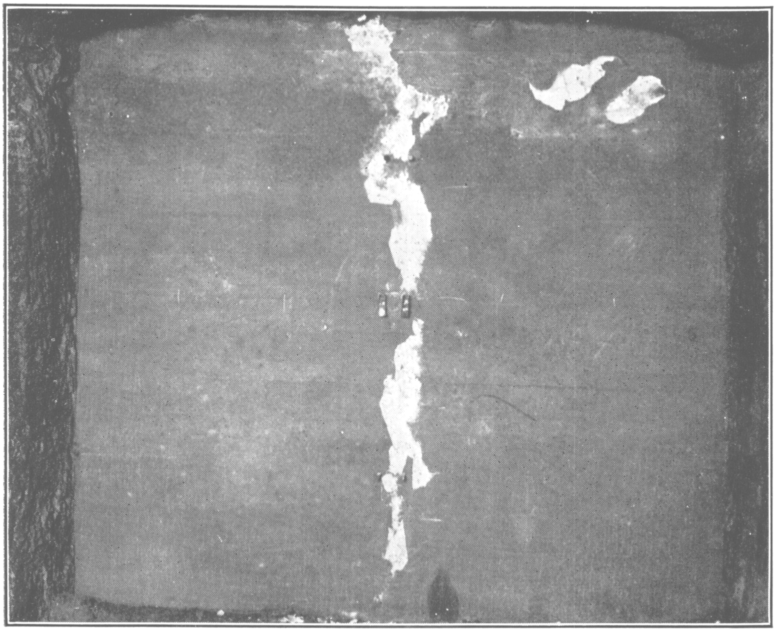

FIGURE 18.—Inner face of stopping 4 after third test

chamber beyond their yield point. A minimum total load of 377,000 pounds was required to produce this effect. The area in compression at the end of the slab was 610 square inches and the average load 6,200 pounds per square inch. The slab was broken considerably at the ends, as Figure 5 shows. The pressure on the slab was 146 pounds, and it is noticeable that neither the slab nor the chamber was damaged by the preceding test, in which the pressure was 107 pounds.

The maximum end pressure of a concrete stopping on the coal will vary with a number of factors, principally the pressure required to cause failure, the crushing strength of the concrete, and the compressibility of the coal. The pressure required to cause failure is interconnected with the others. Thus, if the coal compresses greatly the restraint is reduced, greater movement of the concrete is possible, the tension crack becomes deeper, the area of concrete in compression becomes less, and lower unit pressure on the stopping will cause failure. Any attempt to compute end pressure from the angular movement of the two halves of the stopping must take into account compression in the concrete itself, or the result will be erroneous and the compression of the concrete can not be estimated properly unless the distribution of stress therein is known. It may be possible to effect some analysis of the problem by recently developed theory[13] but such treatment is beyond the scope of the present paper. The stopping and its coal buttresses in combination must in general be considered an indeterminate structure whose strength is determined primarily by the ability of the coal to resist compression and thus prevent movement of the concrete. The stresses in the coal apparently are much less than its ultimate bearing strength. The stoppings may produce pressures on the coal as high as 3,000 to 4,000 pounds per square inch, but this is only a fraction of the bearing strength determined for the Pittsburgh bed. Other beds may have a lower bearing strength, but one would expect this to be accompanied by greater compressibility, and the latter probably would continue to be the governing factor.

CONCLUSIONS REGARDING STRENGTH OF CONCRETE STOPPINGS

The various tests which have been described and discussed show what arrangements were necessary in the Experimental mine to construct a plain massive concrete stopping that would withstand an explosion pressure of 50 pounds per square inch. It remains to determine in what ways the test conditions may differ from those encountered in mines where duplication of the results is desired. The principal variables will be the strength of the concrete, the compressibility of the coal, the strength of the roof and floor, and the size of the passageway.

The strength of the concrete varies with a large number of factors, such as the proportions of cement, aggregate, and water, kind of aggregate, thoroughness and uniformity of mixing, age, and conditions of aging. It is probable that concrete prepared in a producing commercial mine frequently may be weaker than that used

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[13] Cross, Hardy, The Column Analogy: University of Illinois Eng. Exp. Sta. Bull. 215, 1930, 75 pp.

in the tests, because the conditions of preparation will be less favorable, there may be less control of the mixing operations, and the aggregate may have lower mechanical strength. The amount of variation can not be foretold and it is necessary to provide some additional strength to offset it. This is done readily by providing additional restraint or anchorage at the floor and roof. The effect of age will be to give additional strength. It is known that well-made concrete increases in strength for possibly 2 years, and at the end of that time may be 50 per cent stronger than it was at an age of 1 month. This gain is offset by the fact that there is no knowledge when the stopping will be subjected to the stress it is designed to withstand. An explosion may happen a week after it is placed, or it may never happen. A stopping a week old would fail at pressures which one a month old would withstand. Although age is a favorable factor, no reliance can be placed on it.

The compressibility tests have shown that Pittsburgh coal is strong when in place in the bed. Conditions are certainly different in beds in other coal fields where the coal may be stronger or on the other hand more friable and softer. Until tests of the compressibility of other beds have been made it will be necessary to provide additional strength in stoppings erected in mines working friable coal to offset any reduction caused by the weaker coal against which the concrete is buttressed. Restraint or anchorage at the roof and floor is usually the best way of accomplishing this.

The width of most mine passageways is greater than their height, and with the exception of rooms the width generally is not over 15 feet. Greater widths are found at times, and in the thick coals of the West the height may be greater than the width. It was pointed out that there was no definite evidence which would limit the span of a stopping under the rule of behavior found in the experiments, but it is considered wise to limit the span to 30 feet for economic reasons. Stoppings of longer spans should be designed individually, with the use of reinforcing or central buttresses to effect economy.

With these precautions in mind it has been possible to prepare specifications for a plain concrete stopping, use of which will result in a stopping capable of withstanding a pressure of 50 pounds, as required by the operating regulations. If greater strength is desired, the ratio of thickness to span may be altered as indicated in Figure 34.

SPECIFICATIONS FOR A PLAIN CONCRETE STOPPING TO WITHSTAND A PRESSURE OF 50 POUNDS PER SQUARE INCH

The following specifications are limited to stoppings having a span of 30 feet or less. Stoppings with longer spans probably will not be required frequently, but each should receive special consideration and the construction determined by the particular conditions of the case:

Preparation of place.—As far as may be possible a place shall be chosen where the coal ribs are solid and not affected by long exposure or excessive weight of the overlying strata. All loose coal shall be removed from the ribs for at least 3 feet on either side of the point where the stopping is to be placed, making the ribs as straight as possible. The floor shall be cleaned for an equal distance and any loose material removed. All loose roof shall be taken down, and in general ribs, roof, and floor at the site selected shall be as sound and solid as conditions of the strata will permit.

Proportions of the stopping.—The clear distance between the ribs shall be measured after loose material has been trimmed away; this distance is the clear span of the stopping. The thickness of the stopping shall be not less than one-tenth of the clear span. When the height of the passageway is considerably greater than the span it may be advisable to use a somewhat thicker stopping, say a ratio of 1 to 8. The width and depth of the recesses in the ribs shall be equal to the thickness of the stopping. If the coal bed is particularly soft or broken it will be advisable to have the thickness not less than one-eighth of the span and the depth of the recesses 2 feet or more. The thickness of the stopping shall never be less than 12 inches.

Cutting the recesses.—The recesses in the ribs shall be marked off according to the dimensions determined by the span of the stopping and carefully cut by hand. Care must be taken not to shatter the coal on the sides of recesses, and the outer corners must be left as square as possible. The inner corners shall be cut back square.

Preparation of roof and floor.—A trench shall be cut in the floor between the two recesses. It shall be as wide as the recesses and extend into them. The depth of the trench shall be not less than 12 inches and shall extend through all loose material. If the material is too hard to cut with a pick, the following shall be substituted. Holes 18 inches deep shall be bored along the center line at intervals of not more than 18 inches and steel rods seven-eighths inch diameter or more by 36 inches long grouted in them.

It is not advisable to cut a trench in the roof, both because it makes planes for shearing along which the roof material may break and because the space cut in the roof can not be properly filled with concrete. As an equivalent method of tying to the roof, holes 1⅛ inches or larger in size shall be drilled in the roof along the center line of the stopping at intervals of not more than 18 inches and shall be not less than 18 inches deep. Iron rods of seven-eighths inch diameter shall be driven into stiff grout in these holes; the length of these rods shall be such that at least 12 inches will project downward into the stopping.

Building the form.—The form shall be constructed tightly of good lumber properly braced and tied to prevent movement while the concrete is placed and is setting. The ends of the forms shall be flush with the edges of the recesses and shall not extend into them. It will be found advantageous to complete the form on the side opposite to that from which the concrete is placed, and in shutting off inaccessible workings this procedure is necessary. On the near side the studding, braces, and ties shall be completed and the form boards placed to about half height. The remainder of the boards shall be cut and placed so that they are readily available for insertion as needed.

Mixing the concrete.—The concrete shall be not leaner than 1 part cement, 2 parts clean sand, and 4 parts clean gravel or broken stone (1:2:4) by volume. It shall be mixed thoroughly by hand or machine so as to be homogeneous and so that all material will be wet properly; only enough water shall be used to give the stiffest consistency that can be properly spaded in the form. Overwatering must be avoided, as it reduces the strength of the concrete.

Placing the concrete.—Any water that has collected in the trench in the floor shall be bailed out before the concrete is placed. The concrete shall be well spaded, as it is placed in the form, by edged wooden paddles or some other convenient device. Care shall be taken to fill the recesses completely. The concrete shall be placed in successive horizontal layers from one buttress to the other. There shall be no pause greater than one-half hour in mixing and placing the concrete for the entire stopping. However, if there is an unavoidable delay, steel rods ⅞ inch or more in diameter shall be set vertically in the last layer about 18 inches apart and projecting upward 8 inches or more. When the roof is approached the spading will be more difficult, but it must not be neglected. The concrete shall be well worked around the iron rods projecting from the roof. The final form board on the side from which the concrete is placed shall be set in short sections, beginning at the ribs, and the concrete rammed back into the space so that it is tight against the roof. The final portion at the center shall be not over 2 feet wide, and as much stiff concrete as possible shall be placed in this space.

Finishing the stopping.—The form shall not be removed for at least four days after the concrete has been placed. Not later than seven days after the concrete has been placed the top boards and framing on the side from which the concrete is placed shall be removed and any voids at the roof filled by ramming and plastering. This work should be done with a cement gun if available.

STOPPINGS OF MATERIAL OTHER THAN MASSIVE CONCRETE

The foregoing specifications can be applied only to massive concrete stoppings; that is, to stoppings made of concrete placed all at one time. Fireproof stoppings can also be made of brick or concrete blocks, but nothing definite is known of their strength. No recommendation of such structures can be made in the absence of experiments to determine their proper construction for strength. It is, of course, common knowledge that masonry arches of cut stone develop very considerable strength, but as concrete is always available and simply constructed it is naturally the material that should be considered first.

SUMMARY

The United States Bureau of Mines and the United States Bureau of Standards have jointly conducted an investigation of the strength of plain concrete stoppings for coal mines, with the following results:

1. A stopping buttressed against solid-coal ribs acts as a flat arch and develops much greater strength than would be expected on the assumption that it is a beam.
2. The ends of the stopping are restrained, which places a zone of the concrete in compression. This zone may be visualized as arch-shaped, with the convex side of the arch tangent to the center of the stopping face which receives the pressure. The ends of the arch are against the coal ribs, and the concave side of the arch has a common junction with the tension side of the stopping and the coal ribs. Tests of one stopping indicated that the zone of compression had a thickness at the center of possibly 20 per cent of the stopping.
3. A stopping properly buttressed at the ends fails only when the concrete at the center of the face to which pressure is applied is crushed.
4. The strength of such a stopping is sufficient to permit the use of plain concrete without requiring excessive thickness when the pressure to be withstood does not exceed 50 pounds per square inch.
5. The relation of strength to ratio of thickness to span is shown in Figure 34. The ratio of thickness to span must be 1 to 10 to withstand a pressure of 50 pounds, as required by the operating regulations governing coal mines of leased lands of the public domain. If higher pressures are to be withstood, the thickness relative to the span may be increased according to the line of safe values given in Figure 34, or reinforcement may be used if that is more economical.
6. Specifications for the construction of such a stopping have been drafted and are given on preceding pages.
7. As the strength of an unreinforced stopping acting as a flat arch depends upon the ability of the coal ribs to withstand crushing and give only small compression under loads up to 3,000 or 4,000 pounds per square inch, it was desirable to determine the horizontal compressibility of the Pittsburgh coal bed. It was found that pres-

sure exerted over small areas caused the face of the coal to deflect, compressing the material behind it. Part of the compression was elastic and was recovered when the pressure was removed; the balance was permanent set and was not recovered. The results were affected considerably by the size of the area in compression, and the absolute value also depended upon the number of cycles of compression and release made, but approached a constant value as the number of cycles increased. It was found that differences in compressibility at different heights in the bed and over such horizontal distances as could readily be obtained were negligible when its strength as a buttress was considered. It was important, however, that the coal should not be disturbed, as by blasting, weathering, or strata pressure.

The ultimate bearing strength of the coal, which could be determined over an area only 2 inches square because of the limitations of the apparatus, was found to be about 14,000 pounds per square inch. This is much higher than has been determined previously in testing machines; but it must be remembered that the bearing strength will depend upon the manner of loading, the size and shape of the loaded area, and the amount of restraint offered by the surrounding material. Lack of such restraint in specimens tested earlier permitted them to break along the cleats traversing them and was doubtless responsible for the low crushing strength obtained.

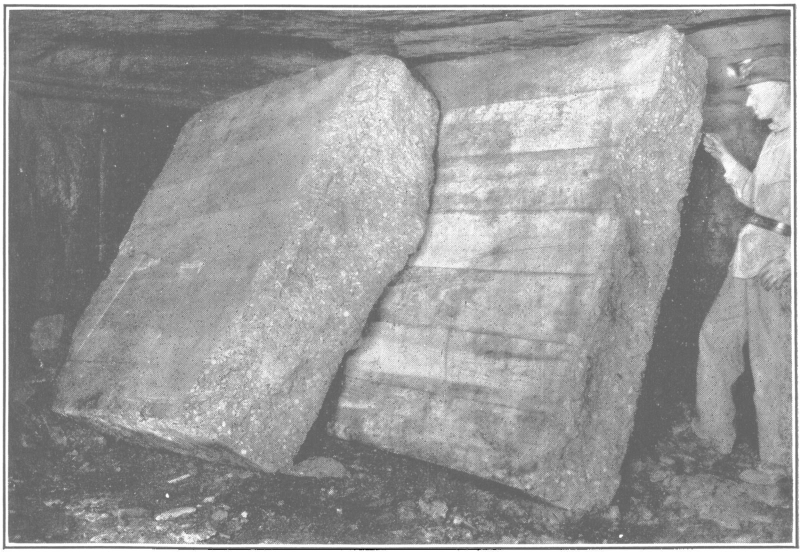

FIGURE 35.—Débris of stopping 7, viewed from original position

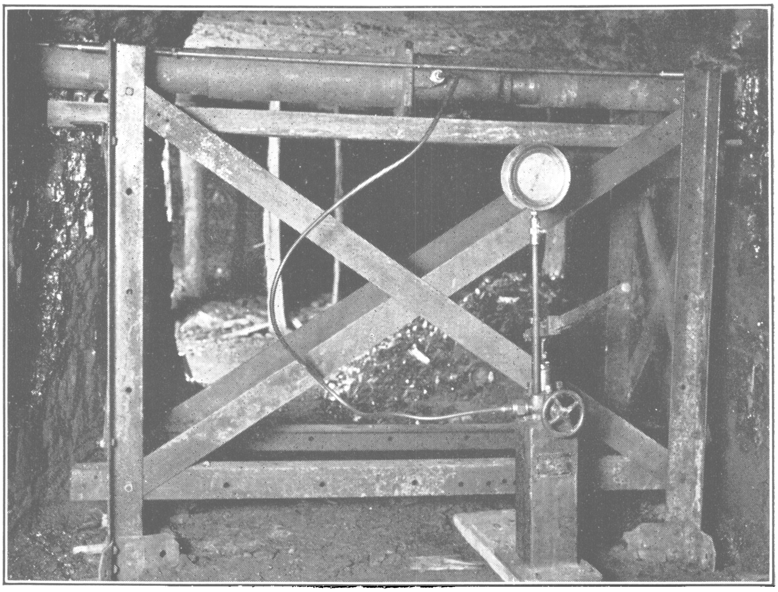

FIGURE 36.—Apparatus used in tests of compressibility of Pittsburgh coal bed

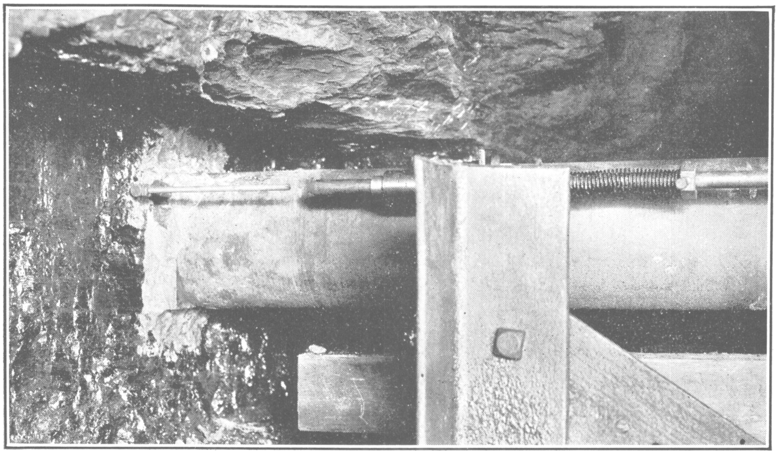

FIGURE 37.—Close view of apparatus at one rib, showing first method of measuring deflection

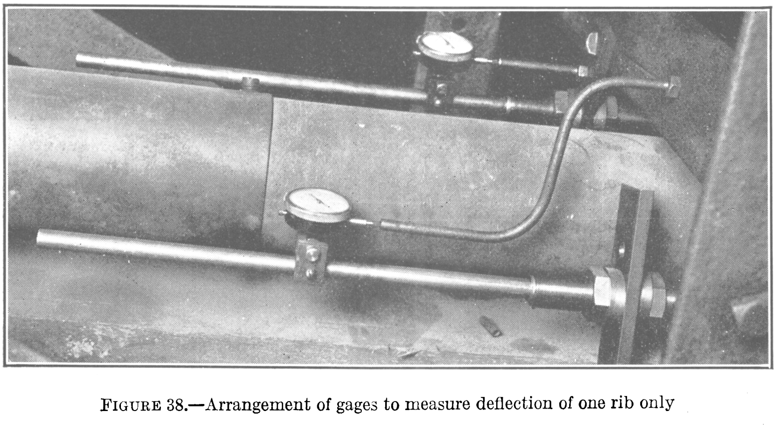

FIGURE 38.—Arrangement of gages to measure deflection of one rib only

APPENDIX.—METHOD OF MAKING COMPRESSIBILITY TESTS OF COAL

Determination of compressibility required a means of applying a series of known loads to the coal over a definite area and a device for measuring corresponding deflection of the coal. The simplest method of applying pressure horizontally was by means of an hydraulic jack and steel cylinders spanning a passageway so that equal pressure was applied to both ribs. The increase in distance between the ribs was then twice the deflection of either rib, if it is assumed that the action was the same at both points. This assumption appeared to be justified where the coal was not altered by pressure or weathering. Determination of the two deflections separately required a fixed point of reference; this method was adopted for some of the later tests in the investigation.

The Pittsburgh coal bed has two sets of cleats or cleavage planes approximately at right angles to each other and the bedding planes. Such cleats are found in many coal beds which have experienced geologic movement after their formation. In the Pittsburgh bed the name "face cleats" is given to the principal set. In direction the face cleats extend southeast and northwest. In the Experimental mine and vicinity the bearing of the face cleats is about S. 67° E. They are pronounced, occur at fairly regular intervals, and extend over considerable distances. The secondary set is called "butt cleats." These are less pronounced and more irregular, and a single cleat does not extend over as great a distance. They do, however, occur closer together and frequently are found to be offset at their junction with the face cleats.

The coal has little strength in tension across either set of cleats or in shear along them. Such shearing resistance as is developed along them on application of load is as likely to be due to friction as to true shear of continuous material. Visible gaps are occasionally found along the cleats, and it may be supposed that spaces of minute thickness exist along all of them.

The application of pressure over a small area perpendicular to one set of cleats produces results that may be likened to those obtained when the end of a pencil is pressed on the center of a large book. The effect is altered in the case of the coal by the presence of the secondary set of cleats. There will always be one of these a short distance on either side of the compressed area. The tendency of the pressure is to bend the surface of the coal, producing a shearing stress in it. There is only limited resistance to this at the free cleats, and the face of the compressed block of coal moves relative to the face of the blocks on either side. The movement is not necessarily confined to a single cleat; it may be distributed over a number.

DESCRIPTION OF APPARATUS

The apparatus used is illustrated in Figure 36. The large steel frame, constructed of angle irons and braces, was used to support the jack and steel cylinders during assembly. When not under pressure they rested on wedges on the plank which appears longitudinally below them. When pressure was applied no support was needed. The jack is seen near the center of the picture, with a copper tube connecting it to the independent pump in the foreground. The capacity of the jack was 60 tons. Pressure was transmitted through steel cylinders; there are two of these to the left and one to the right of the jack in the photograph. The jack was calibrated in a testing machine, and the measured total load agreed satisfactorily with the load computed from the reading of the gage on the pump and the area of the ram. The gage reading was used to determine the load on the coal throughout the work.

The load was applied to the coal through a steel plate 1 inch thick fastened to the end of the cylinder adjacent to the rib. The rib was trimmed at the desired point to remove any coal affected by exposure, and the new surface was made as smooth as possible. The plate was bedded in a thin layer of quick-setting cement mortar and kept under a low load for 24 hours while the cement was hardening. Even distribution of pressure over the surface of the coal in contact with the plate was thus closely approximated. Figure 37 is a close view of the arrangement at one of the ribs. The plate is not wholly visible because of the cement that has been extruded around it, but the lower corner is seen plainly in contrast to the curvature of the cylinder.

Figure 37 also illustrates the first method used to measure deflection of the ribs. A pin screwed into the edge of the plate near one corner carried a short rod which projected parallel to the direction of applied pressure. There was a small gap between the end of the rod and a second rod, which spanned the passageway, was supported in bearings fastened to the framework, and was kept in contact with a similar pin projecting from the opposite plate by a strong spring. Alteration of the length of the gap was the same as the deflection of the two ribs and was measured by a spring gage and micrometer caliper. This method proved to be slow and tedious, and a micrometer dial gage was substituted. It was fastened to one of the rods with its plunger resting against the other. This system had the added advantage that movement could be observed continuously. Measurements were made at diagonally opposite corners of the steel plates, and the average was taken as the deflection of the center. Wide discrepancies in movement of the two corners were taken as an indication of twisting of the plate.

When the movement of the two ribs was measured separately the angle-iron frame was made the fixed point of reference. It was braced firmly against the ribs in such manner that it would not disturb or be disturbed by the area in compression. The arrangement of the dial gages is shown in Figure 38; they were fastened to rods carried by bearings and pressed by springs against the pins projecting from the plate. The plate is to the right of the picture in Figure

38. The plungers of the gages were in contact with other rods firmly fastened to the frame.

TYPICAL TEST RESULTS

Figures 39 and 40 illustrate the results obtained when pressure is applied to a small area of the coal in successive cycles of application and release of load. The results shown in Figure 39 were obtained with undisturbed coal at the location of stopping 6. Two cycles of application and release of load are shown. The pressure plates were 5.87 inches square. The curves do not start from zero pressure, as the plates were set under a load of 138 pounds per square inch. The first application of pressure is marked *1*, with an arrow pointing upward. The line is straight in its lower portion and bent downward slightly in its upper. Recovery of the compression lagged considerably as the pressure was released (curve *1*, arrow pointing downward), and there was a permanent set of 0.007 inch when the original pressure was reached. About 0.001 inch of this was removed before the second cycle was started; but no significance is attached to this, as close control of low pressures was not possible with the apparatus used. The second cycle is similar to the first, but the hysteresis loop between increasing and decreasing pressure is smaller. Total deflection and permanent set both increased about 0.003 inch. The maximum pressure used was about 2,500 pounds.

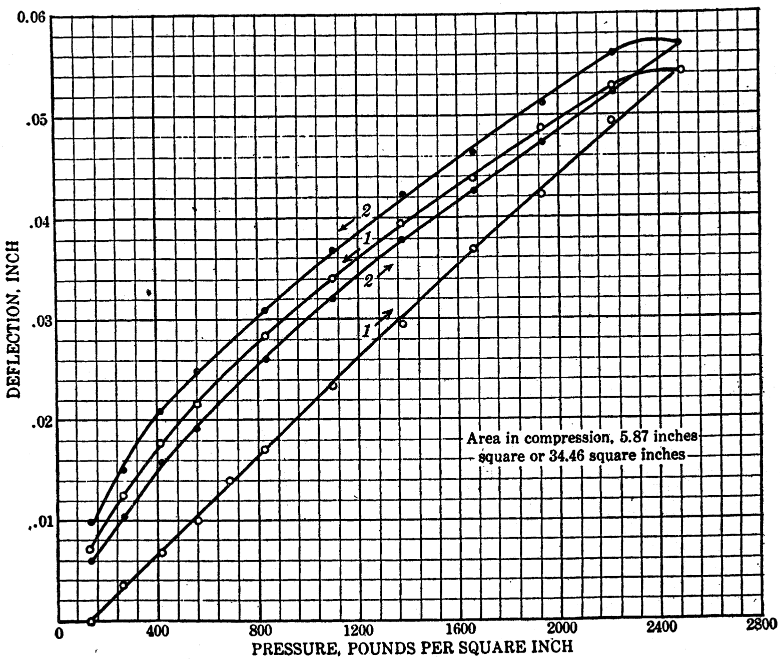

FIGURE 39.—First two cycles of compression of coal at place of stopping 6

Figure 40 shows five compressions of the coal at stopping 6. The decompression half of the cycles has been omitted to avoid confusion, and the first two cycles are those shown in Figure 39. It is seen that the permanent set at the beginning of the fourth cycle was slightly less than at the beginning of the third. The difference is at present assumed to be the limit of error of experiment, and complete removal of permanent set is postulated. This is supported by the fact that there was only a slight increase in total deflection at a pressure of 2,500 pounds. The fourth cycle was continued to a pressure of 3,450 pounds, the maximum obtainable with the 60-ton jack. The curve bends upward in the new range as additional permanent set is being placed in the coal, as shown by the difference in initial deflection between the fourth and fifth cycles. The fifth cycle has the same relation to the fourth that the second does to the first, and additional cycles to a pressure of 3,450 pounds would result in rapidly decreasing increments to the permanent set and the establishment of an elastic cycle of compression and decompression. The curves of compression and decompression do not coincide; even when no additional set is incurred there is always a hysteresis loop.

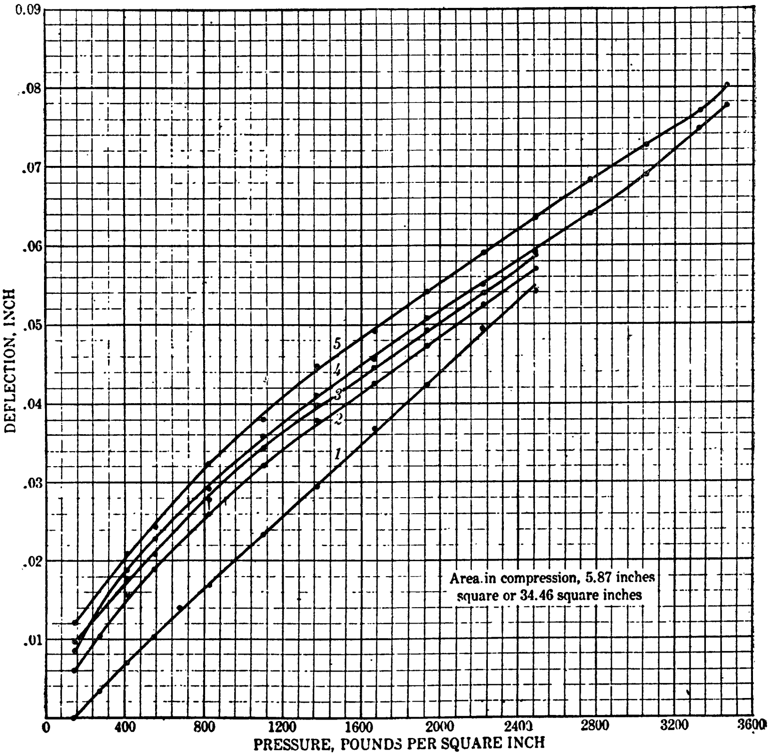

FIGURE 40.—Five compressions of coal at place of stopping 6

The effect of variation of size of area compressed on the compression caused by a given pressure is illustrated in Figure 41. Curves

1 to *3* show the deflection obtained on initial compression with plates whose respective areas were 144, 47.6, and 14.7 square inches. Curve *1* was limited by the capacity of the jack. The striking point is the large increase in compression obtained as the area in compression is increased. The second point is the bend in curve *3* near its origin. Similar results have been obtained in a number of instances, and an explanation is yet to be obtained. Curves *2* and *3* have been extrapolated to zero pressure and curve *3* in two different ways, one of which follows the bend whereas the other ignores it. One may expect that the compression obtained will be related to both the area and perimeter of the plate through which the pressure is applied, as the action around the perimeter is mainly shear while that under the center is mainly direct compression. It will be necessary to have data at higher pressures obtained with plates of other sizes and shapes, particularly rectangles, before a quantitative application can be made to the buttressing of stoppings. Detailed consideration of the results will appear in a separate paper.

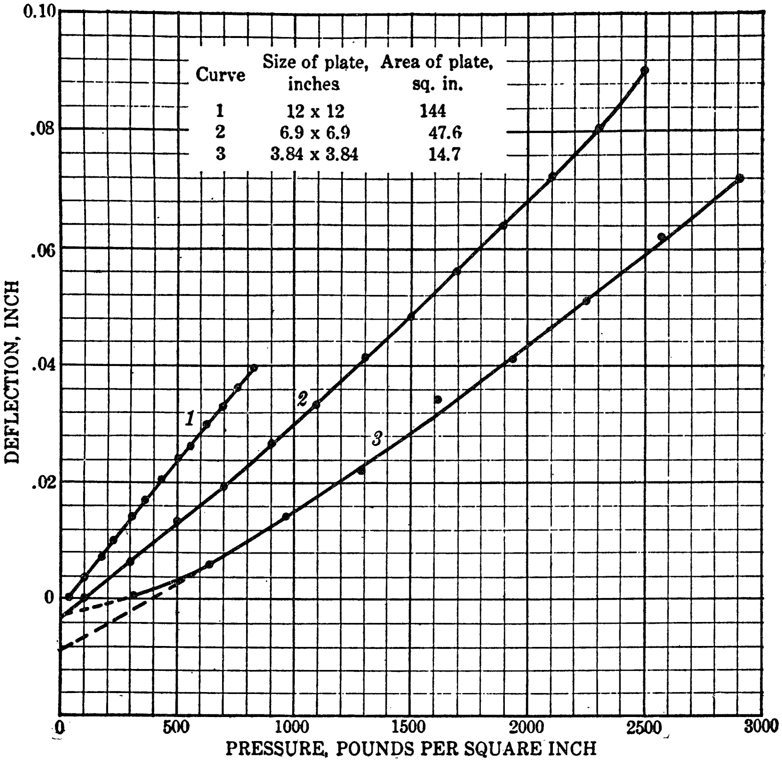

FIGURE 41.—Relative deflection of coal ribs with different areas in compression for same vent pressure