RESEARCH REPORT

CENTRIFUGALLY CAST STAINLESS STEEL
FIBER-REINFORCED REFRACTORY PIPE

to

U. S. Bureau of Mines

December 29, 1975

Battelle
Columbus Laboratories

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FINAL REPORT

on

CENTRIFUGALLY CAST STAINLESS STEEL FIBER-REINFORCED REFRACTORY PIPE

to

U. S. Bureau of Mines

December 29, 1975

by

Charles W. Kistler, Jr., David R. Lankard,
and J. Richard Schorr

Contract No. H0252064

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Contract No. H0252064

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Very truly yours,

Dale E. Niesz

Dale E. Niesz, Manager
Ceramic Materials Section

DEN:mfl
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FOREWORD

This report was prepared by Battelle, Columbus Laboratories, Columbus, Ohio, under USBM Contract No. H0252064. The contract was initiated under the Bureau of Mines Metallurgy Program. It was administered under the technical direction of Metallurgy with Mr. Martin H. Stanczyk acting as the Technical Project Officer. Mr. J. J. Arnold was the contract administrator for the Bureau of Mines.

This report is a summary of the work recently completed on this contract during the period June 1, 1975, to December 29, 1975. This report was submitted by the authors on December 29, 1975.

ACKNOWLEDGMENT

The work described in this report was conducted principally by personnel in the Ceramic Materials Section of Battelle's Columbus Laboratories of which Dr. Dale E. Niesz is Manager. Mr. Charles Kistler, Jr., served as Principal Investigator on the program, and Jack E. Reichelderfer was the Principal Technician. Appreciation is also extended to Merle Rhoten and Clara Nothstine, of the Fabrication and Quality Assurance Section, for the X-radiographic characterization.

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SUMMARY

Pipe specimens 4 inches in outside diameter were made from a stainless steel fiber-reinforced tabular-alumina refractory castable by centrifugal casting techniques. Specimens were fabricated from a castable mix containing up to 5.20 weight percent (1.96 volume percent) preblended fibers, and by introducing the castable and fibers separately. Fibers were 0.013 inch in diameter and 3/4 or 1 inch long. The degree of fiber orientation and distribution was assessed by radiographic examination of the 1/2-inch-thick pipe walls. The speed of the mold (centrifugal force) during the time the mix was being introduced into the mold was found to be a significant variable affecting consolidation of the material, with the best results being obtained at low speeds (240 rpm or 3.2 g). Introducing the preblended mix into a spinning mold gave a more uniform fiber distribution than when the mix was palced in a stationary mold and then spun to distribute the material. Preferential orientation of the fibers in a circumferential direction was obtained by introducing the castable and fibers separately, using a compartmentalized feed trough to orient the fibers as they were fed into the mold. Longitudinal orientation was not obtained, but was considered technically feasible with proper casting parameters. For applications in which specific directional properties are required, the use of continuous reinforcement such as wire mesh was considered more practical than a

unidirectional fiber orientation because properties would be more uniform and predictable. A uniform distribution of fibers in a planar orientation (random in plane of pipe wall) can, however, be readily achieved by centrifugal casting fibrous mixes, and should be advantageous for many applications, especially where crack control is needed.

INTRODUCTION

This program was initiated to develop a self-supporting ceramic pipe for use in coal-gasification systems. Ideally, the pipe would be impermeable and strong enough to replace steel pipe which is susceptible to corrosion by acidic species in the product gas. However, a more reasonable objective would be a preformed ceramic pipe which could be used as a liner inside the steel pressurized shell, but the liner must have properties superior to those of castable refractories now used for this application.

Precasting unreinforced liners would permit (1) nondestructive inspection of each piece before use, thus insuring a high degree of control over quality of components going into a gasification system, and (2) prefiring of the shapes to obtain high-strength bodies with better erosion resistance compared with that of the unfired castable. In either cast or fired form, preformed liners would be highly susceptible to field breakage, especially in lengths above several feet. However, the preformed liners could be inserted into pipe sections and cast-in-place with an insulating backup castable. The use of a preformed liner would eliminate the need for any type of mold form (metal, cardboard, etc.) commonly used to line pipes in the field. The liner would simply be inserted in the pipe, centered, and backed up with an insulating castable. This method of installation would eliminate the need for maintaining a mold inventory, and would permit rapid relining of pipes during shutdown.

Unreinforced ceramic pipe liners would not, however, have any advantage over cast-in-place linings with respect to spalling resistance, and would be susceptible to handling damage. By incorporating discontinuous steel fibers in the material, the toughness of the pipe can be improved severalfold, and, thus, would lead to improved impact resistance and improved resistance to damage by thermal shock.

The properties may be improved to such an extent that the liner could be supported by stand-offs at intervals within a steel pipe, without the need for a backup material. In this case, the annular space between the ceramic liner and the pressure-containing steel pipe could be purged to eliminate corrosion of the mild steel, and the liner would actually be "self-supporting".

Fabricating a steel-fiber-reinforced liner by centrifugal casting was known to be feasible and was the sole approach to be pursued in demonstrating that a fiber-reinforced pipe can be produced. Although the approach was to develop methods for introducing and dispersing discontinuous stainless steel fibers in preferred orientations (circumferentially and longitudinally), attainment of a high degree of unidirectional reinforcement is not necessary for obtaining mechanical- and thermal-shock resistant composites, especially if a planar orientation is obtained as a result of centrifugal casting. However, for some applications, it may be desirable to orient discontinuous fibers rather than to add continuous reinforcement, so the feasibility of doing so was evaluated in this program.

Fiber-reinforced pipe liners formed by centrifugal casting have other advantages that could prove quite attractive to coal-gasification system designers. First, thin-wall pipes can be fabricated which are strong enough to handle and which will remain intact in service. Rather than lining steel pipes with 2 or more inches of a castable, a preformed pipe liner with 1-inch-thick walls may be suitable. The net result is that smaller-diameter steel pipes can be used for pressure containment, or higher flow rates can be obtained in existing systems. Second, centrifugally cast concrete is known to have higher strengths and densities compared with vibratory-cast material, and these characteristics are desirable for maximum erosion/abrasion resistance. It is doubtful whether erosion/abrasion resistance would be improved with a fibrous mix, although resistance to impact, thermal stress, and spalling would be greater.

The fabrication of preformed liners containing stainless-steel fibers restricts any subsequent firing to a temperature much above 2000 F, which is not sufficient to develop a ceramic bond in state-of-the-art high-alumina castables. However, by selecting appropriate densification aids, it may be possible to develop nonequilibrium liquid phases which promote sintering and form a more erosion-resistant liner.

In summary, a reinforced ceramic pipe liner, preformed by centrifugal casting, has several attractive features compared with cast-in-place liners, namely:

(1) Potential for quality assurance via NDT

(2) Simplified on-site assembly, since forms are not required

(3) Significant improvements in resistance to spalling from either mechanical or thermal shock

(4) Reduced wall thickness and weight

(5) Higher strengths and densities

(6) Potential for improved erosion/abrasion resistance via prefiring and/or chemical bonding.

The objective of this program was to demonstrate the fabricability of thin-wall (1/2 inch) ceramic pipes containing preferentially oriented stainless steel fibers. A state-of-the-art refractory castable was used as a model material.

TECHNICAL DISCUSSION AND RESULTS

Literature Search

The open, government, and patent literature was searched to identify methods that could be used to introduce or orient chopped fibers in centrifugal casting processes. Centrifugal processing is used in a variety of industries, but very little information was uncovered which dealt with uniaxial fiber orientation techniques (other than the planar orientation which is obtained as a result of gravitational forces).

The open literature abstracted in Chemical Abstracts and Engineering Index was computer searched from 1972 and 1970 to present, respectively, for information related to centrifugal casting. Of over 200 abstracts retrieved, most dealt with centrifugal casting of metals. Others dealt with the fabrication of glass-reinforced silos, waste dewatering processes, particle size analyses, crystal separation, and so on. None of these references appeared useful and neither source referenced U.S. Patent 3,689,614, which was known to be pertinent. Chemical Abstracts was also hand searched from 1972-1926, but only a few articles were uncovered and none pertained to fibrous composites.

The Government literature abstracted by National Technical Information Services (NTIS) was computer searched back to 1964 with similar results, except that a few abstracts dealing with improved impregnation of fibers by metal matrices through centrifugal processing were reported. Only 42 abstracts were uncovered in this period, which indicated that the Government literature was not a good source of information.

Because of the rather poor results obtained from the above searches, hand searching of earlier literature was not attempted, nor was the Department of Defense literature searched. Instead, the U. S. patent literature was searched back to 1963 with somewhat more success. Class 264, dealing with "plastic and nonmetallic article shaping or treating" contained the most pertinent abstracts, especially those in subclasses 60, 108, 114, 228, 270, 310, and 311, which were the major categories searched. The period 1975 back to 1968 was searched, and several patents were identified which dealt with orienting discontinuous fibers.

The combing technique described in U. S. Patent No. 3,608,134 was not considered a very practical approach for use within a rotating mold on a production basis, and was considered only as a backup procedure.

The extrusion process described in U. S. Patent No. 3,651,187 had merit as a means of aligning fibers in a concrete mix on a production basis, but the process must be considered as an alternative to centrifugal casting rather than a simple alignment method. U. S. Patent No. 3,714,312 appeared to contain useful information in that circumferential fiber alignment is imparted by rotating the mold at a speed such that the mix slides down the side of the mold. U. S. Patents 3,359,350 and 3,475,532 described, respectively, a modified combing procedure and the introduction of fibers into a mold at a high velocity. U. S. Patent 3,250,831 described a magnetic process for orienting magnetic particles, but this technique did not appear to be practical either. Although the patent literature identified several fiber-alignment techniques, most required the construction of complex auxiliary equipment and/or could not be used within the 3-inch-ID pipes that were to be fabricated. Because a simple process was desirable from the experimental work as well as for any future production operation, only techniques that would not complicate the centrifugal casting process were considered further.

The literature search covered only the relatively narrow topic of centrifugal casting because a considerable amount of literature on and experience with the properties and applications of steel-fiber-reinforced concrete were already available at Battelle.[(1-11)*] Some of this literature dealt with centrifugal casting[(1)] and techniques for obtaining unidirectional fiber alignment[(9)]. This literature was reviewed early in the program before selecting the approaches to be studied.

Literature dealing with fiber composites is extensive, and even a survey of this literature was not considered practical. However, several bibliographies[(12)] were scanned, and a few articles dealing with metal-fiber-reinforced cement were identified. There were a few articles in the literature which dealt with fiber-reinforced, chemically bonded ceramics[(13)]. These articles were reviewed because chemical bonding (as discussed above) is one method of obtaining a more erosion-resistant material, but no discontinuous fiber orientation techniques were uncovered.

Experimental Approach

Several methods of imparting fiber alignment were considered before proceeding with the construction of centrifugal casting molds and feed troughs for use with a Battelle-owned centrifugal casting machine. Approaches (2), (3), (5), (6), and (7) discussed below were evaluated to some extent during the course of the program. To demonstrate that realistic-size components can be produced, and to permit multiple samples to be obtained from each pipe produced, the ancillary equipment was designed to produce specimens 3-inches in ID x 4 inches in OD x 30 inches long. The approaches considered were:

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* References are listed on Pages 22 and 23.

(1) Introducting a preblended mix and combing it to provide a circumferential fiber orientation. This method was not considered attractive because it was felt that the comb would tend to form furrows which would have to be subsequently consolidated and the combing would have to be done in thin layers to prevent bridging of fibers and tear out of fiber-rich areas. In addition, the technique would be useful for only obtaining a circumferential orientation.

(2) Introducing the fibers and refractory castable separately either through troughs or tubes. This method would be desirable in that it might be possible to obtain fiber volume loadings higher than those obtainable with premixed batches and with minor changes the process could provide either longitudinal or circumferential fiber orientation. However, on the basis of prior experience in handling fibers, it would be difficult to transport the fibers and/or disperse them without balling. In addition, the technique would tend to produce a layered composite unless the castable and fibers were introduced simultaneously, but space limitations severely limit this concept. The fibers and castable could be alternately introduced into the mold by feeding each from an inclined trough in the laboratory, but this would be cumbersome as an industrial process. With either a laboratory size or an industrial-size process, uniform control of fiber feed rate would be difficult.

(3) Utilizing velocity gradients to orient fibers while transferring material from a transfer tube or tray to the rotating mold. Some preferential fiber orientation could be obtained, especially with high-aspect-ratio fibers, but the process would be applicable only for circumferential orientation unless the fibrous mix is preoriented. Preorientation was considered a separate technique and is discussed below.

(4) Feeding the preblended mix through slots in a transfer tray. This technique was proposed as a means of obtaining preferential fiber orientation, but was not considered to be very feasible because of the tendency for fibers to bridge slots; space limitations inside a 3- or 4-inch-ID pipe which limits the depth of any Vee-shaped hopper section; particularly in the circumferential direction; and the difficulty in obtaining a uniform feed rate over the length of the tray.

(5) Preorienting fibers in a premixed batch before introducing the batch into the casting mold. Hoppers and/or slotted troughs could be used to discharge material into a transfer tray which would be introduced into the spinning mold and then tipped to discharge the material. Either circumferential or longitudinal fiber orientations would be obtained with the same basic equipment. Although the technique has flexibility and simplicity, fiber orientation during material discharge

and consolidation must be maintained. Extrusion of a preblended mix to obtain longitudinal fiber orientations would be one variation of the basic process. Because of the flexibility imparted by orienting the fibers outside the mold, and the ability to use the same transfer tray for either preoriented or random fiber mixtures, this technique was selected as the major fabrication process to be evaluated. Obviously, Method (3) could have an effect on the results obtained, depending on the rotational speed of the mold, and the fiber aspect ratio.

(6) Using a compartmentalized feed trough which would tend to orient a preblended fibrous mix as it is discharged into the mold. This technique might be considered as a supplement to technique (3), but was thought to have some merit of its own.

(7) Vibratory casting a preblended mix to impart a fiber orientation followed by consolidation in the centrifugal-casting apparatus. This technique was considered too complicated for production operations but was, experimentally, relatively simple and worthy of evaluation since vibration is known to orient fibers.[9]

Description of Equipment

Figure 1 illustrates the feed trough assembly and molds attached to a Battelle-owned variable-speed centrifugal-casting apparatus. The unit is capable of speeds from 240 to 1200 rpm by adjusting a variable-speed motor pulley. Gravitational forces associated with mold speed for specimens of various diameters are shown in Figure 2. Rotational speeds registered on the rpm meter shown in Figure 1 were verified with a strobe-light tachometer early in the program.

The pipe molds shown in Figure 1 were made from split pipes to simplify specimen removal. The molds slip into a recessed hole in the caster drive plate for centering, and are bolted to the drive plate through tabs welded on the side. A disk with a 3-inch hole is bolted to the open end of the mold to control the wall thickness of the pipe specimen during centrifugal casting.

In addition to the plain feed trough shown in Figure 1, a compartmentalized feed trough was constructed for orienting the fibers as they are discharged by rotating the trough. This feed trough is shown schematically in Figure 3, in a clockwise discharge position. The saw-tooth design was selected because preliminary fiber-feeding experiments with V-shaped compartments having a 90-degree included angle indicated that fibers flowing down opposing faces tended to bridge at the bottom of the V and fall off in clumps. With the saw-tooth design, this problem was minimized. Dimensions of the compartments were selected to permit feeding fibers 1-1/2-inches long, or shorter.

Pins (rather than compartments) spaced along the edge of a plain trough were also tried in cursory experiments, but fiber bridging was encountered at spacings less than the fiber length. At high spacings, the pins were not very effective in orientating the fibers and caused clumping and irregular flow. Much better feeding control was obtained with the compartment design.

The inclined pan located above the feed trough in Figure 1 was designed with a narrow (1/2 inch wide) discharge chute (not visible) to preorient a fibrous mix as it was vibratory fed onto the feed trough. It was used in only one experiment and was removed from the assembly for most of the evaluations.

Materials Used and Mix Design

A commercial tabular-alumina castable* containing a high-purity calcium aluminate hydraulic-cement binder was used almost exclusively throughout the program. It is typical of the type of material being used to line "hot" transfer lines in coal-gasification systems currently under development, and is commonly used in a variety of other applications. A wet-sieve analysis of the material was obtained and this is given below:

Tyler Screen	Weight Percent
+6	3.6
6/8	14.4
8/14	13.2
14/28	10.2
28/48	10.6
48/100	11.8
100/200	9.0
-200	27.2 (difference)

Stainless steel fibers** 0.013-inch in diameter and 3/4- or 1-inch long were used for all of the fabrication experiments. This material combination could be considered a model system for studying fabrication parameters in this program, but it is also developing as a practical refractory system for monolithic applications where mechanical- or thermal-shock damage resistance is required.[3,7]

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* Harbison-Walker Castolast G.

** Obtained from National Standard Co., Niles, Michigan.

Fiber volume loadings representative of a practical material were selected for evaluation purposes. Both the fiber size and volume loadings selected for use in the preblended mixes were typical of those that have been found to provide optimum properties in Wirand® * concrete mixes. Theoretically, mechanical properties of composites containing discontinuous fibers can be predicted[5,6,7] by an equation of the type

$$\sigma_c = A\sigma_m V_m + B\sigma_f V_f \left(\frac{l}{d}\right) ,$$

where A and B = constants
σ_m = stress in matrix
V_m = volume-fraction matrix
σ_f = stress in fiber developed by the interfacial bond
V_f = volume-fraction fibers
l/d = fiber aspect ratio (length/diameter).

However, the formula applies only within the range where fiber orientation and matrix density can be maintained uniformly. Practically, workability problems arise when long fibers are used and/or at high volume loadings, as shown in Figure 4. One can extend the workability area somewhat (shift curves toward upper right) by increasing the water content of the mix, but this degrades the mechanical properties, which are strongly influenced by the water/cement ratio, even for fired castable refractories. Similarly, the workability area in Figure 4 is reduced (curves shifted to lower left) if lower water/cement ratios are used, or if coarse aggregate is used in the mix. Because conventional concretes contain coarse aggregates, fiber aspect ratios and volume loadings used in most field installations fall within the lower left portion of the "optimum property" area of the diagram.

In Figure 4, the shape of the workability-limit curves approximates a curve of "equal properties" one can predict from the above equation if only the contribution from the fibrous reinforcement is considered. For example, the lower workability-limit curve approximates a volume fraction/aspect ratio product of about 1.6. Because matrix volume fraction and properties are assumed to be constant, this is only an approximation, but it can serve as a guide in selecting a particular type of fiber and/or loading.

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* Wirand® is a registered trademark of the Battelle Development Corporation.

Initial experiments were conducted with a mix formulation (2.7 volume percent of 3/4 x 0.013-inch fibers) having an aspect-ratio/volume-fraction product of about 1.6, but difficulty was encountered in handling this mix. Consequently, more workable formulations with a product of 1.0 were selected for use throughout the program. These mixes, shown as circles within the "optimum" area of Figure 4, contained 0.96*, 1.30, and 1.75 volume percent of 1-1/4-, 1-, and 3/4-inch fibers, respectively, assuming that the castable had a typical fired bulk density of 160 pcf. A fired bulk density (rather than dried) was used so that the weight percentage of matrix corresponded to the amount of dry castable required in each mix. Because the centrifugally cast specimens had fired bulk densities of about 179 pcf (187 pcf dried), the actual volume fraction of fibers in these mixes would be about 1.08, 1.47, and 1.96 percent, respectively, for the 2.90*, 3.90, and 5.20 weight percent fibers used in the dry mixes.

Water requirements for unreinforced tabular alumina mixes are typically in the 8 to 9 percent range when the material is to be vibratory cast, and in the 9 to 10 percent range for "spade" casting. With the fiber additions selected, it was found that a 10 percent water level (dry castable basis) was required to obtain a mix which would have adequate workability without bleeding on vibration. With the water content based only on the weight of dry castable used, a constant water:cement ratio** could be maintained for the different mixes without affecting workability. In a few experiments, water contents above 10 percent were used.

Specimen Curing and Drying

In order to permit reuse of the two pipe molds on a daily basis when desired, all specimens fabricated during the program were steam cured at 135 F overnight. They were then radiographed and stored at ambient conditions until the end of the program, when selected specimens were wet sectioned by diamond sawing. If dry-bulk-density measurements were made, the sectioned pieces were then dried overnight at 240 F. All program deliverables were also dried at 240 F prior to shipment.

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* 1-1/4-inch fibers were not actually used in the experiments.

** Assuming 20 percent cement in the Castolast G, the water:cement ratio would be 0.50.

Specimen Characterization

Visual examinations, bulk-density measurements, and X-radiography were the methods used to characterize the pipe specimens, and, normally, only those specimens that were well consolidated were radiographed. Figure 5 is a schematic of the device used to obtain radiographs normal to the pipe wall so that an undistorted image of the reinforcement could be obtained. Contact prints made from selected radiographs shown in a subsequent section of the report are oriented with the longitudinal axis of the specimen parallel to the long dimension of the page.

Fabrication Results

Preblended Mixes

For discussion purposes, the results are discussed according to fabrication technique although they were not conducted in such order chronologically. Specimen numbers can be used to trace the chronological testing order if desired. These numbers correspond to page numbers in Battelle's Laboratory Record Book No. 32028.

Vibratory Cast Control Samples. A few specimens were prepared by vibratory casting pipes in a vertical position, using 3-inch-OD brass tubing as a core in the 4-inch-ID pipe molds removed from the caster. Specimens 4, 5, and 23 listed in Table 1 were formed in this manner. Radiographic examination revealed that the fiber distribution and orientation were far from uniform. Fibers are oriented in a longitudinal direction in some areas, but are random and/or circumferentially oriented in an adjacent area where the mix flow pattern was different. Areas where longitudinal orientation is most pronounced are fiber lean, while those where the orientation is random are fiber rich. The fibrous mix appears to flow in "clumps" which are probably present, but unnoticed, in the preblended mix.*

* Fibers are sprinkled into the castable after it has been wet mixed about 3 minutes. It is then blended an additional minute with the fibers. A better distribution may be obtainable by preblending the fibers and dry mix in a can, and then wet mixing in the Hobart.

As Figure 6 illustrates, this poor orientation/distribution was also obtained in a subsequent specimen (No. 23) vibratory cast prior to spinning for densification. For this specimen, the mix was carefully fed through a funnel to provide a uniform feed rate and flow into the vibrating mold. Even with additional care in filling the mold, and the use of stronger vibration, the fiber orientation and distribution was still very nonuniform. Because of the rather poor results obtained and the complications introduced into a rather simple process by the use of a cored mold, vibratory casting, and then mold transferral to the caster, effort was directed to other approaches.

Centrifugal Casting. In this section, the results of experiments conducted with both a stationary and spinning mold are discussed.

Stationary mold. Because flow of the preblended mix was observed to be at least partially effective in imparting a fiber orientation in vibratory casting, an experiment was performed to see whether flow of the mix around the mold circumference could induce some fiber orientation. The procedure involved feeding the mix into a stationary mold in three batches (Specimen 24 in Table 1), each batch charged at the same location so as to emphasize any irregularities imparted by the process. The pipe was fabricated easily and visually appeared to be of good quality. Radiographic examination* revealed (Figure 7) that fibers had concentrated randomly on the 3 o'clock side of the pipe (edges of Figure 7), while the 9 o'clock side (center of Figure 7) was fiber lean and had only a limited amount of circumferential orientation. The 6 o'clock (bottom) and 12 o'clock (top*) sides were even more fiber lean than the 9 o'clock side. This approach did not appear to have much merit because the fiber distribution was nonuniform compared with that obtained when the mold was spun while feeding the mix.

Spinning Mold. With this technique, the preblended mix was also fed into the mold by rotating the feed trough, but the mold was spinning. IU all cases, the feed trough was vibrated to help discharge the material. Most experiments were conducted using a plain angle-iron feed trough, although some were conducted with the compartmentalized feed trough shown in Figure 3 and discussed earlier.

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* "B" and "T" in Figure 7 indicate bottom and top of pipe, respectively, while charging the mold.

A series of specimen (Nos. 12 through 15 in Table 1) were centrifugally cast at different feeding speeds early in the program to determine whether mold speeds could be used to impart a circumferential fiber orientation. Ironically, the fiber distribution obtained was essentially random in the plane of the pipe wall and, unlike the vibratory-cast specimens, highly uniform. The uniform distribution is related to the uniform distribution of material into the mold as it is vibrated off the edge of the V-shaped feeder trough. In contrast to later experiments, no problems were encountered in casting specimens at high (20 to 40) G levels, and all four specimens appeared to be of good quality. Radiographs of "good quality" specimens are presented below.

Although not shown in Table 1, some effort was spent in studying whether the preblended mix could be vibrated through a V-shaped trough with a slotted bottom. Results were discouraging as the castable went through the slots while the fibers bridged over and stayed in the trough. This approach was discarded as impractical because wide slots required to permit feeding would not effectively orient the fibers.

An attempt was also made to impart a longitudinal fiber orientation by preorienting the mix as it was fed onto the feeding trough (Specimen 22 in Table 1). To do this, a V-shaped inclined pan with a narrow (1/2 inch wide) discharge chute was used to vibrate the mix onto the feed trough rather than simply load it by hand. The feed trough was moved ahead manually to match the feed rate of material coming from the pan's discharge chute. Problems were encountered with the mix "hanging up" in the discharge chute, with the result that the material discharged onto the trough was not well oriented nor uniformly distributed. The material was slowly vibrated into the spinning mold off the edge of the feed trough following the same procedure used for the four pipes made without the preorientation. However, the result was quite disappointing as the pipe specimen (No. 22, Table 1) was poorly consolidated and had large voids extending completely through the pipe wall in some areas. The poor results can be attributed to two factors: (1) a gradual "set up" of the castable during the 20 minutes or so required for mixing and feeding the material before final consolidation was started and (2) partial consolidation of the preoriented mix, so that it did not flow off the trough as uniformly as a randomly oriented mix. This specimen was of such poor quality that it was not radiographed.

The rest of the experiments conducted with preblended mixes are summarized in Table 2. The compartmentalized-feed-trough experiments (Nos. 33 through 40 in Table 2) were conducted in an attempt to impart a circumferential fiber orientation, but extremely poor mix consolidation was obtained, even when the water content was increased to 10-3/4 percent in Specimen 39 (Figure 8).

In subsequent experiments (Nos. 41 through 55 in Table 2), the plain feed trough was used and mold speed was reduced in an attempt to achieve the good results obtained in earlier experiments.* Generally, however, the specimen quality was poor until the mold speed was reduced to the minimum value (240 rpm = 3.2 G) obtainable with apparatus. Good-quality specimens (Nos. 55 through 59 in Table 2) were then consistently obtained. Dry bulk-density measurements made by a mercury-displacement technique on small pieces cut from these specimens (results column in Table 2) did not reveal any advantage to the use of high G forces for final consolidation. In fact, the specimens formed at 5 G's were slightly more dense on the basis of the single data point obtained from each sample.** Figure 9 shows two of these pipe specimens sectioned to illustrate differences in wall textures and fiber distribution through the wall thickness. The reason for fiber concentration near the outer wall of Specimen 55 is unknown, although it may be related to the clockwise rotation of the feed trough. All of the other specimens in this series (Nos. 56 through 59) had a more uniform fiber distribution across the wall thickness, as illustrated by Specimen 57 in Figure 9. In the plain of the pipe wall, Specimens 55 through 59, all had a relatively uniform, but random, fiber distribution, as the radiograph in Figure 10 illustrates.

The experiment on Specimen 60 in Table 2 was conducted to determine whether the compartmentalized feed trough could be used to impart a preferential orientation with the "optimum" process parameters, but again poor results were obtained.

The fiber-containing mix did not flow well enough to "level out" before consolidating, and irregularities formed in feeding were retained in the specimen. The quality of this specimen was better than that of the specimen shown in Figure 8, but significantly inferior to the quality of those shown in Figure 9.

The reason why good quality pipes (e.g., No. 12) obtained early in the program could not be duplicated at a later date is not completely known. However, the most likely reason for this discrepancy is believed to be the minor differences in feeding techniques used by the operator and an over-ranking of the original specimen quality. Early in the program the feed trough was vibrated while it was loaded, which tended to uniformly fill the trough. Later in the program, the feed trough was not vibrated until the trough was actually rotated, and the trough fill may not have been as uniform. In addition, the rates of material discharge could have been controlled more carefully as the operator was becoming familiar with the apparatus. On reexamining Specimens 12 through 15 and comparing them with Specimens 55

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* The same technician performed all of the experiments conducted during the program.

** Using a dry bulk density of 186.6 pcf measured on an unreinforced centrifugally cast specimen, the fiber colume percent for these mixes back-calculates to about 2.0 volume percent, which agreed with the extimate made in the section on Mix Design.

through 59 made late in the program, the only pipe specimen made early in the program which had a quality similar to the others was the one spun at 5 G's (Specimen 12). Those made at 20 and 40 G's (Specimens 13 through 15) were not as well consolidated, which confirms the findings made in other experiments that high G levels during feeding are undesirable.

Unreinforced Mixes

Midway through the program when poor consolidation was being encountered with the fibrous mixes, several experiments were conducted without reinforcement to determine what processing factors were most effective in consolidating a mix. These are summarized in Table 3 and are briefly discussed below.

The experiments conducted with the compartmentalized feed trough revealed that low mold speeds and counterclockwise (CCW) rotation of the feed trough were more important process parameters than water content of the castable. However, to obtain a good-quality pipe, the plain feed trough was required so that the mix was evenly distributed. With the plain trough, CCW rotation was again observed to provide superior pipes. To completely avoid irregularities in the pipe-specimen wall, the mix also could be charged into a stationary mold and then spun to distribute the material. The unreinforced specimens were not characterized except for dried and fired-bulk-density data obtained from the best specimen (No. 46).

Fibers and Castable Introduced Separately

Preliminary experiments conducted using this procedure were disappointing (Specimens 31 and 32 in Table 4), but after learning how to obtain good consolidation by lowering the mold speed while feeding, good results were obtained with Specimen 61 (shown in Figure 11). As Table 4 indicates, it was possible to use six full charges of castable in this pipe. Figure 12 shows that some circumferential fiber alignment was obtained, although many of the aligned fibers were in rows. Compared with pipes prepared from preblended mixes (Figure 10), the fibers in this pipe were not distributed as uniformly, and some "clumps" are evident.

In observing the fibers as they were fed from the compartmentalized trough in forming this specimen, the first three charges of fibers appeared to tumble in the mold after striking the previously deposited castable layer. However, during the last three charges, the fibers appeared to be smoothly drawn off the feed trough as they contacted the castable. This effect may have produced a more preferential fiber orientation near the inside wall, compared with the outside wall, which was not apparent from the ratiograph or on visual examination of sections cut from the pipe. Two methods of evaluating how the gap between the feeder trough and the pipe wall affects fiber orientation can be suggested. One method is to form thin-wall specimens at various gap dimensions by either moving the feed trough sideways, or by placing liners of various thickness in the pipe mold. The other is to use fibers somewhat longer than the gap. In the case of Specimen 61, the initial gap size was approximately equal to the fiber length (3/4 inch) and most of the fibers would randomly fall off the feed trough until a 1/4-inch layer of castable was built up in the mold. Once the gap is reduced to something less than the fiber length, the fibers will begin to be pulled (rather than fall) off the feed trough and be preferentially oriented. This effect is shown schematically in Figure 13.

Although the use of a compartmentalized feed trough produced nearly ideal fiber orientation while feeding, the fiber "pickup" phenomena described above was also expected to apply to fibers fed off a plain feed trough. Even if the fibers do not slide off in a completely transverse direction, if they are long enough the leading end should be picked up by the castable wall (especially if it is wet from water spun out of the mix). With a preblended fibrous mix, the effect would not be expected to work nearly as well because the fibers would have to be pulled out of the castable mix. Figure 14 illustrates that a circumferential fiber orientation was also obtained in Specimen 65 fabricated with a plain feed trough (Table 4).

No experiments were conducted to determine whether a longitudinal fiber orientation could be obtained by feeding the fibers and castable separately. However, on the basis of experience obtained during this program, it would appear that by using a semicircular (rather than V-shaped) feed trough, a longitudinal orientation could be obtained as the fibers roll off the trough. Whether or not this orientation can be maintained as the fibers fall onto a previously deposited castable layer is uncertain, but using a low mold speed and rotating the feed trough clockwise should help obtain the desired longitudinal orientation.

PROGRAM DELIVERABLES

Two 4-inch-long sections from each of the following pipe specimens were delivered to the Bureau of Mines, Tuscaloosa Metallurgy Research Laboratory, Tuscaloosa, Alabama.

Pipe No.	Comments		
23	Vibratory cast and spun		
46	Unreinforced mix		
12			
55	Plain trough	Preblended mix	Spinning mold
56			
57			
58			
59			
60	Compartmentalized trough		
61	Compartmentalized trough; fibers introduced separately		

Except for Pipes 12, 23, and 46, all of the specimens were taken from the section of the pipe which was radiographed, and from areas adjacent to the segments shown in Figures 9 and 11. Pipes 23 and 61 exhibited the most preferential orientation in the longitudinal and circumferential direction, respectively. The other reinforced specimens had a more random distribution of fibers in the plane of the pipe wall. Pipe 65 was fabricated too late in the program to be included in the above shipment of deliverables, but samples can be provided on request.

CONCLUSIONS

The following conclusions were drawn on the basis of work conducted during this program.

(1) Wire-reinforced castables with 5.20 weight percent (1.96 volume percent) of 0.013 x 3/4-inch stainless steel fibers can be centrifugally cast with the fibers either preblended in the mix or introduced separately. Higher fiber loadings are feasible, especially for fibers introduced separately, but these may not be needed, since the loadings employed are typical of those now used in many field applications.

(2) Processing parameters play a critical role in the distribution and consolidation of a fiber-containing refractory castable, especially rotational speed of the mold. Low mold speeds (or centrifugal forces) are needed to obtain a uniform distribution of material in the mold. Some consolidation occurs as the material is distributed, which probably inhibits any subsequent material movement even at high G forces.

(3) The method by which the material is fed into the mold from the feed trough appears to have an effect on consolidation behavior. Allowing the material to be carried upward by the mold probably results in a slower acceleration of the material and permits the mix to be more uniformly distributed compared with the situation where the material is dropped onto the mold.

(4) Good consolidation was consistently obtained at the lowest speed (240 rpm) at which the apparatus was capable of operating without modification. The surface speed of the mold (240 sfpm) and the gravitational forces (3.2 G) imposed on the material after it was accelerated to this speed were probably more important than the rotational speed itself.

(5) Pipe fabrication in a spinning mold is much simpler with a preblended mix than when the fibers and castable are introduced separately. Only one batch of fibers needs to be weighed out, and the actual casting operation can be done in half the time.

(6) Pipe fabrication in a stationary mold is comparable to that in a spinning mold in terms of processing difficulty, but the fiber distribution obtained may not be as uniform for the stationary mold. However, good material distribution is obtained by the stationary mold method.

(7) Fibers can be preferentially aligned in a circumferential direction by feeding the fibers from a feed trough with transverse compartments, and by alternately feeding the castable from a plain trough.

(8) Longitudinal fiber orientation is more difficult to obtain than circumferential and was not successfully demonstrated in this program.

(9) X-radiography is an excellent method of characterizing fiber distribution as well as orientation.

(10) The fiber distribution in pipes made by vibratory casting a preblended mix can be very nonuniform.

(11) Bulk densities obtained by centrifugal casting are about 10 percent higher than those obtained by normal spade-casting procedures. The higher bulk density should improve the erosion resistance of the monolithic materials.

(12) With proper processing procedures, some of the initla mixing water is spun from the castable, and final water contents of about 7 percent or lower are possible. the lower water content should improve the strength of the material over and above that imparted by an increase in density.

RECOMMENDATIONS

This program has demonstrated that 3-inch-ID pipes can be fabricated from a stainless-steel-fiber-reinforced refractory castable mix by centrifugal casting. although it is possible to obtain some degree of preferential fiber orientation by introducing the fibers and castable separately, this procedure is complicated in that (1) multiple batches of fibers must be weighed out for each pipe; (2) alternate additions of fibers and castable are time consuming, requiring almost twice the fabrication time needed with a preblended mix; and (3) fiber feed rates are difficult to control compared with those for a preblended castable and fiber distribution is likely to be less uniform. Discontinuous fibers, rather than conventional continuous reinforcement (such as welded-wire fabric), are usually of interest for specialty applications where the simplicity of use in a preblended mix outweighs their extra cost and lower performance compared with other types of reinforcement. When directional properties are specifically required, it is usually more economical to design a reinforcement cage to provide these properties, and this approach is recommended in lieu of any unidirectional fiber-orientation experiments for any application where specific directional properties are required.

As discussed in the Introduction, preformed refractory pipes made with discontinuous stainless steel fibers have potential for use as liners in coal-gasification systems, and there are several prestressed-concrete manufacturers who have the equipment with which large pipes (10-ft lengths) could be fabricated. If the fabrication parameters for fiber-reinforced castable pipes were developed and made available to these manufacturers, it is likely that one or more would be willing to fabricate pipes on a semi-production basis for refractory manufacturer resale, or specifically for a coal-gasification plant contractor. However, the technology transfer will only occur if the pipes can be fabricated with existing manufacturing equipment. Although much centrifugally cast concrete is prestressed, this type of reinforcement cannot be considered for this application. For this application, discontinuous fibers (or possibly wire mesh) would provide the impact resistance needed for handleability and the thermal-shock damage resistance needed in the coal gasification-environment. Uniformity of fiber distribution would be important and could be obtained more readily with a random fiber orientation in the plane of the pipe wall, such as is obtained by centrifugal casting. This type of fiber orientation would also make the material easier to characterize and design with, because there would be a plane of isotrophy. Consequently, the following approach is recommended for future research on refractory liners for transfer lines in coal-gasification systems:

(1) Optimize fabrication parameters in the laboratory using not only a hydraulic-bonded castable, but also a phosphate-bonded castable which is known to have superior erosion resistance. The fabrication techniques used in this study should be compatible with those a concrete manufacturer could easily adapt, although a pumpable mix and/or different feeding method may be needed. Industrial contacts to characterize equipment used, or easily adapted by prestressed-concrete manufacturers, should be made early in such a program. Wire mesh might be preferred by industry, and, if so, it should be considered along with discontinuous fibers. Some characterization of the mechanical properties of pipes "optimized" on the basis of bulk density and visual characteristics should also be included.

(2) Demonstrate the fabricability of full-size pipes at the production facility of a prestressed-concrete manufacturer and conduct an NDT evaluation of pipe quality. Obtain additional mechanical-property data in the form of full-size bend tests to obtain preliminary bending-moment data needed for specifying handling procedures. Arrange for a pilot-plant trial of pipes made from the two types of castables to obtain information on installation characteristics, thermal shock, and erosion resistance.

(3) Disseminate the fabrication technology developed to the energy-conversion community, to concrete manufacturers having centrifugal-casting capabilities, and to the refractories industry.

SUBJECT INVENTIONS

A method by which some degree of circumferential fiber alignment can be obtained using a specific centrifugal-casting technique has been identified. This improvement is obtained by introducing the fibers separately with a compartmentalized feed trough designed to impart a transverse-fiber orientation, and using fibers long enough to bridge the gap between the feed trough and the castable layer previously deposited in the mold. The process, shown schematically in Figure 13, may also be envisioned to work with a noncompartmentalized feed trough (as illustrated). This improvement is being separately reported on Forms DI-1216 and DI-1217.

Before this improvement was realized, plans had been made to present a technical paper at The American Ceramic Society's annual meeting, May 1-6, 1976, in Cincinnati. The results of this program would be presented in a session dealing with refractories, possibly one directed to energy conversion. The following abstract was submitted on November 19, 1975, but acceptance of the paper has not yet been received.

"Four-inch-diameter pipe specimens were fabricated from a tabular alumina-refractory castable containing chopped stainless steel fibers. Specimens were fabricated by various techniques to determine whether the centrifugal casting process could be used to impart a preferential fiber orientation. X-radiography was used to characterize fiber distribution and orientation obtained. Processing procedures and their effect on pipe quality and fiber distribution will be discussed."

Permission to present a technical paper based on this program will be formally requested in the near future. It is anticipated that most of the fibures shown in this report would be used in the presentation.

REFERENCES

(1) Burnett, E.F.P., Constable, T., and Cover, P., "Centrifuged Wire Fiber Reinforced Concrete", in Fiber Reinforced Concrete, American Concrete Institute Publication SP-44, pp 455-475 (1974).

(2) Snyder, M. J., and Lankard, D. R., "Factors Affecting the Flexural Strength of Steel Fibrous Concrete", Amer. Concrete Inst., Jour. Proceedings, 69 (2), 96-100 (1972).

(3) Lankard, D. R. and Sheets, H. D., "Use of Steel Wire Fibers in Refractory Castables", Bull. Amer. Ceram. Soc., 50 (5), 497-500 (1971).

(4) Shah, S. P. and Rangan, B. V., "Fiber Reinforced Concrete Properties", Amer. Concrete Inst. Jour. Porceedings, 68 (2), 126-135 (1971).

(5) Swamy, R. N.,"Flexural Strength of Steel Fiber Reinforced Concrete", Proc. Inst. Civil Engrs., 57 (2), 701-707 (December, 1974).

(6) Lankard, D. R., "Prediction of the Flexural Strength Properties of Steel Fibrous Concrete", in Fibrous Concrete-Construction Material for the Seventies, by B. H. Gray, G. R. Williamson, and G. B. Batson (Department of the Army, Construction Engineering Research Laboratory, Champaign, Illinois), Conference Proceedings M-28, pp 103-123 (December, 1972).

(7) "State-of-the-Art Report on Fiber Reinforced Concrete", American Concrete Inst. Jour. Proceedings, 729-744 (November, 1973).

(8) Shah, S. P. "New Reinforcing Materials in Concrete", Amer. Concrete Inst. Jour. Proceedings, 257-262 (May, 1974).

(9) Hannant, D. J. and Spring, N., "Steel-Fiber Reinforced Mortar: A Technique for Producing Composites With Uniaxial Fiber Alignment", Magazine of Concrete Research, 26 (86) (March, 1974).

(10) Naaman, A. E. and Shah, S. P., "Tensile Tests of Ferrocement" Amer. Concrete Inst. Jour. Proceedings, pp 693-698 (September, 1971).

(11) Krenchel, H., "Fiber Reinforced Brittle Matrix Materials", in Fiber Reinforced Concrete", American Concrete Institute Publication SP-44, 45-77 (1974).

(12) (a) Rauch, H. W., Sr., and Sutton, W. H., "Bibliography on Ceramic Fibers and Fibrous Composite Materials", DCIC Report 69-4, Part I, Literature (AD 701118), and Part II, Patents (AD 701119).

(b) Fleck, J. N., "Bibliography on Fibers and Composite Materials--1969-1972", MCIC Report 72-09 (AD 746214).

(c) Manufacturing Methods of Composite Materials, Volume I, (AD 701500), (February, 1970).

(d) Rauch, H. W. Sr., et al., "The Fabrication, Testing, and Application of Fiber-Reinforced Materials: A Survey", AFML-TR-68-162 (AD 841952) (September, 1968).

(13) (a) Chase, V. A., et al., "Metallic Filaments and Their Composites", in Advanced Fibrous Reinforced Composites, 10th SAMPE Symposium, San Diego, California, (November 9-11, 1966).

(b) Greszcuk, L. B., and Leggett, H., "Development of a System for Prestressing Brittle Materials", Douglas Aircraft Company, Report DAC-3670 (N67-39851) (1967).

TABLE 1. RESULTS OF CENTRIFUGAL-CASTING EXPERIMENTS USING 3.90 WEIGHT PERCENT OF 1 x 0.013-INCH STAINLESS STEEL FIBERS PREBLENDED IN CASTOLAST G[(a)]

Pipe No.[(b)]	Description of Experiment	Feeding: G's	Feeding: Minutes	Feeding: No. Charges[(c)]	Final Consolidation: G's	Final Consolidation: Minutes	Results
4	Vibratory cast-control sample	Weak vibration	ND	Continuous	None	-	Fiber distribution poor, but longitudinal orientation obtained in some areas
5	Ditto	Ditto	ND	Ditto	None	-	
12	Vibratory feed of mix into spinning mold	5	6-7	4-5, CW	5	5	Feeding trough vibrates against sample during last two charges; material tends to roll between trough and sample; more rigid feeder trough required; no preferential fiber orientation but distribution quite uniform; mold sealing critical at high G levels to prevent loss of water from mix; samples all good quality
13	Ditto	20	6-7	4-5, CW	20	5	
14	"	20 (repeat)	6-7	4-5, CCW	20	5	
15	"	40	6-7	4-5, CCW	40	5	
22	Longitudinal preorientation of mix on feeding trough before feeding into spinning mold	5	15	6, CCW	5	5	No vibration or roll problems with rigid angle-iron feeder trough; preorientation not uniform on trough; mix set up and did distribute in mold; sample quality very poor.
23	Mold filled by vibratory casting in vertical position prior to spinning	Strong vibration	3	Continuous	40	5	Mix fed slowly down sides of funnel in attempt to get longitudinal fiber orientation from mix flow; some orientation obtained but distribution poor; no water spun from mix
24	Vibratory feeding of mix into stationary mold	5 (1-min spin between charges)	6	3, CCW	20	5	Water spun from mix left in mold between charges to aid mix distribution; mold charged at same location (6 o'clock) each time; fibers concentrated randomly on 3 o'clock side; 9 o'clock side fiber lean but showed slight circumferential orientation

(a) Water content of 10 wt % castable basis (9.5 wt % total dry-weight basis) was used in all experiments; 3.90 wt % is 1.47 vol % fibers, total dry-weight basis.
(b) Corresponds to page number in Laboratory Book 32028.
(c) Feeding trough rotation direction also indicated; mold always rotating clockwise.

TABLE 2. CENTRIFUGAL-CASTING EXPERIMENTS CONDUCTED WITH STAINLESS STEEL FIBERS PREBLENDED IN CASTOLAST G

Pipe No.(a)	Mix: Wire	Mix: Water(b)	Feeding: Trough	Feeding: G's	Feeding: Minutes	Feeding: No. Charges(c)	Final Consolidation(c): G's	Final Consolidation(c): Minutes	Results	
33	5.20 wt % - 3/4 x 0.013 in.	10	Compartmentalized(d)	5	7-1/2	8, CW	5	5	Mix very fluid in mixer, but builds up ridges in mold; poor consolidation of material, even at high water contents; no water spun from any of these specimens, even though water content was high and none leaked from mold; feed trough hit material after last charge for most mixes.	
34	5.20 wt % - 3/4 x 0.013 in.	10	Compartmentalized(d)	20	7	8, CW	20	5		
37	5.20 wt % - 3/4 x 0.013 in.	10-1/2	Compartmentalized(d)	20	6	7, CW	20	5		
39	5.20 wt % - 3/4 x 0.013 in.	10-3/4	Compartmentalized(d)	20	6	7, CW	20	5		
40	3.90 wt % - 1 x 0.013 in.	10-3/4	Compartmentalized(d)	20	6	6, CW	20	7		
41	5.20 wt % - 3/4 x 0.013 in.	10-3/4	Plain Vee	20	5	6, CW	20	5	Ridge problem less pronounced, but consolidation still poor; feed trough rotation not important; specimens formed at 5 G's appeared somewhat better than one formed at 20 G's.	
51	5.20 wt % - 3/4 x 0.013 in.	10	Plain Vee	5	3-1/2	6, CCW	5	5		
52	3.90 wt % - 1 x 0.013 in.	10	Plain Vee	5	5-1/2	6, CW	5	16		
53	3.90 wt % - 1 x 0.013 in.	10	Plain Vee	5	6	6, CCW	5	5		
55	5.20 wt % - 3/4 x 0.013 in.	10	Plain Vee	3.2	4-1/2	6, CW	5+20	1+5	Fibers concentrated near outside wall; inside wall rough; about 1/3 mixing water spun out; 193.9 pcf.	Good quality pipes, but no evidence of preferential fiber orientation; final water content of pipes in 6-1/2 to 8 percent range.
56	5.20 wt % - 3/4 x 0.013 in.	10	Plain Vee	3.2	5-1/2	6, CCW	5	5	Inside wall rough; about 1/3 mixing water spun out and poured out of mold; 197.1 pcf.	
57	5.20 wt % - 3/4 x 0.013 in.	10	Plain Vee	3.2	5	6, CCW	20	5	Inside wall smooth in areas; about 1/5 of mixing water spun out; 192.8 pcf.	
58	5.20 wt % - 3/4 x 0.013 in.	10	Plain Vee	3.2	5	6, CCW	5+10+20	2+2+2	Inside wall smooth in areas; about 1/4 mixing water spun out; 192.2 pcf.	
59	5.20 wt % - 3/4 x 0.013 in.	10	Plain Vee	3.2	5	6, CCW	10	5	Inside wall rough; about 1/4 mixing water spun out; 193.1 pcf.	
60	5.20 wt % - 3/4 x 0.013 in.	10	Compartmentalized(d)	3.2	5	5, CCW	5+10+20	2+2+2	Poor consolidation; feed trough hit material during 4th charge; very uneven wall.	

(a) Corresponds to page number in Laboratory Book 32028.

(b) Weight percent castable basis.

(c) Mold rotation always clockwise.

(d) Feed trough positioned against stop during each charging so that material was fed into mold at same point to accent irregular fiber distributions imparted by feed trough.

TABLE 3. CENTRIFUGAL-CASTING EXPERIMENT WITH UNREINFORCED CASTOLAST G

Pipe No.[a]	Mixing Water[b]	Feeding				Final Consolidation		Results
		Trough	G's	Minutes	No. Charges[c]	G's	Minutes	
42	10-1/2	Compartmentalized	20	5	7, CW	20	13	Very poor consolidation of mix; material builds up in rows similar to those shown in Figure 8
43	11	Compartmentalized	20	5	6, CW	20	5	
44	10	Compartmentalized	5	5	7, CW	5	15	Fair consolidation, but ridges still evident
45[d]	10	Compartmentalized	5	4	6, CW	5	5	
46	10	Plain	5	5	6, CCW	5	17	Good consolidation; 186.6 pcf dried-bulk density
47[e]	10	Plain	5	6	3, Stationary mold	5	5	Good consolidation
48	10	Plain	5	4	6, CW	5	10	Fair consolidation
49	10	Compartmentalized	5	5-1/2	7, CCW	5	5	Fair consolidation, but definitely better than Samples 42 and 43

(a) Corresponds to page number in Laboratory Book 32028.

(b) Weight percent castable basis.

(c) Mold rotation always clockwise.

(d) Another commercial tabular alumina castable used, but behaved similar to Castolast G.

(e) Mold stopped at same location for each charging.

TABLE 4. CENTRIFUGAL-CASTING EXPERIMENTS WITH FIBERS AND CASTOLAST G INTRODUCED SEPARATELY

Pipe No.[a]	Mix		Feeding				Final Consolidation		Results
	Wire	Water[b]	Trough	G's	Minutes	No. Charges[c]	G's	Minutes	
31	5.20 wt % - 3/4 x 0.013 in.	10	Plain (castable) Compartmentalized (fibers)	5	11	5 castable, CW 4 fibers, CW	5	5	Castable did not consolidate well and no water spun from mix; pipe quality poor; feed trough hitting material did not permit 6 charges castable, 5 of fibers as planned.
32	5.20 wt % - 3/4 x 0.013 in.	10	Plain (castable) Plain (fibers)	5	9	5 castable, CW 4 fiber, CW	5	5	
50	5.20 wt % - 3/4 x 0.013 in.	10	Plain (castable) Compartmentalized (fibers)	5	7	4 castable, CCW 3 fiber, CCW	5	16	
61	5.20 wt % - 3/4 x 0.013 in.	10	Plain (castable) Compartmentalized (fibers)	3.2	11-1/2	6 castable, CCW 5 fiber, CCW	5+10+20	2+2+2	No trough/material contact; good consolidation; 1/6 to 1/3 mixing water spun out; some circumferential fiber orientation obtained.
65	5.20 wt % - 3/4 x 0.013 in.	10	Plain (castable) Plain (fibers)	3.2	10	"	"	"	

(a) Corresponds to page number in Laboratory Book 32028.

(b) Weight percent castable basis.

(c) Mold rotation always clockwise.

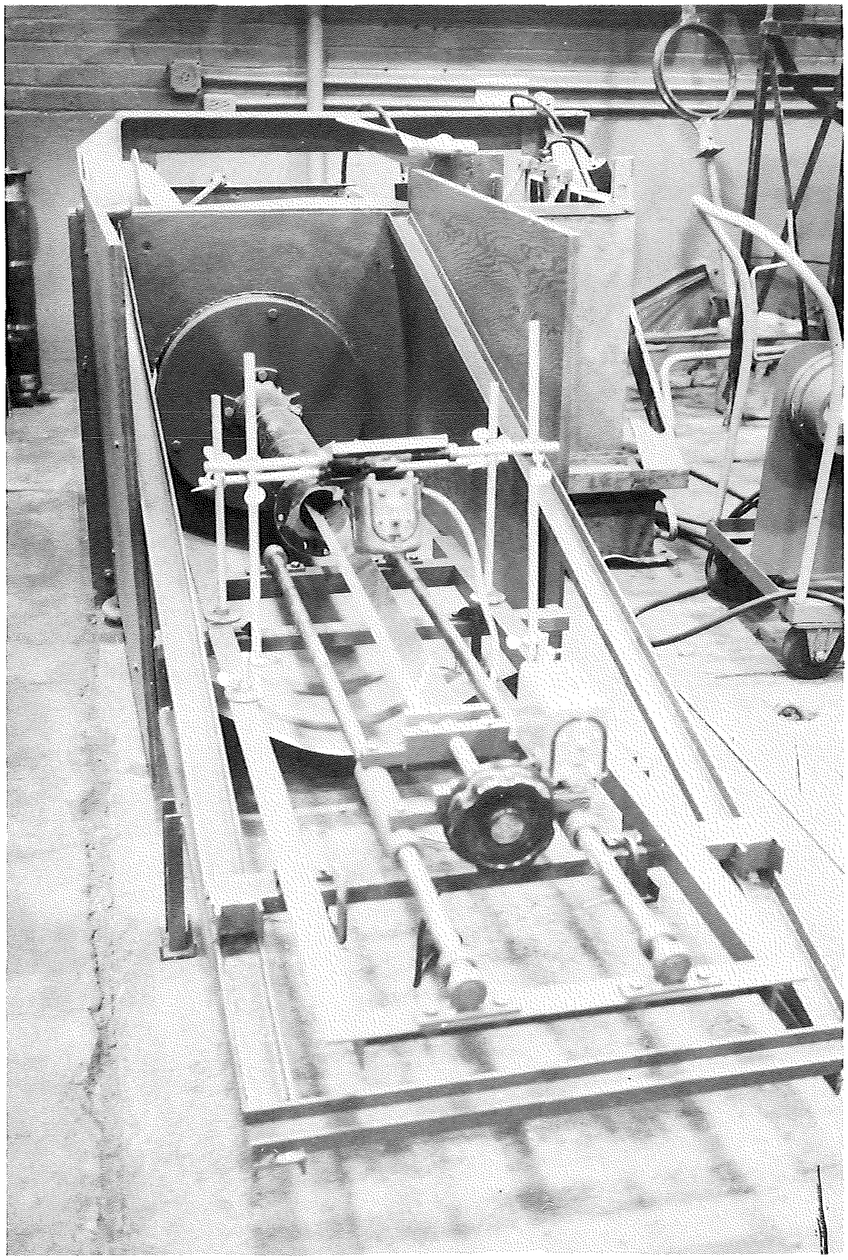

FIGURE 1. CENTRIFUGAL-CASTING APPARATUS

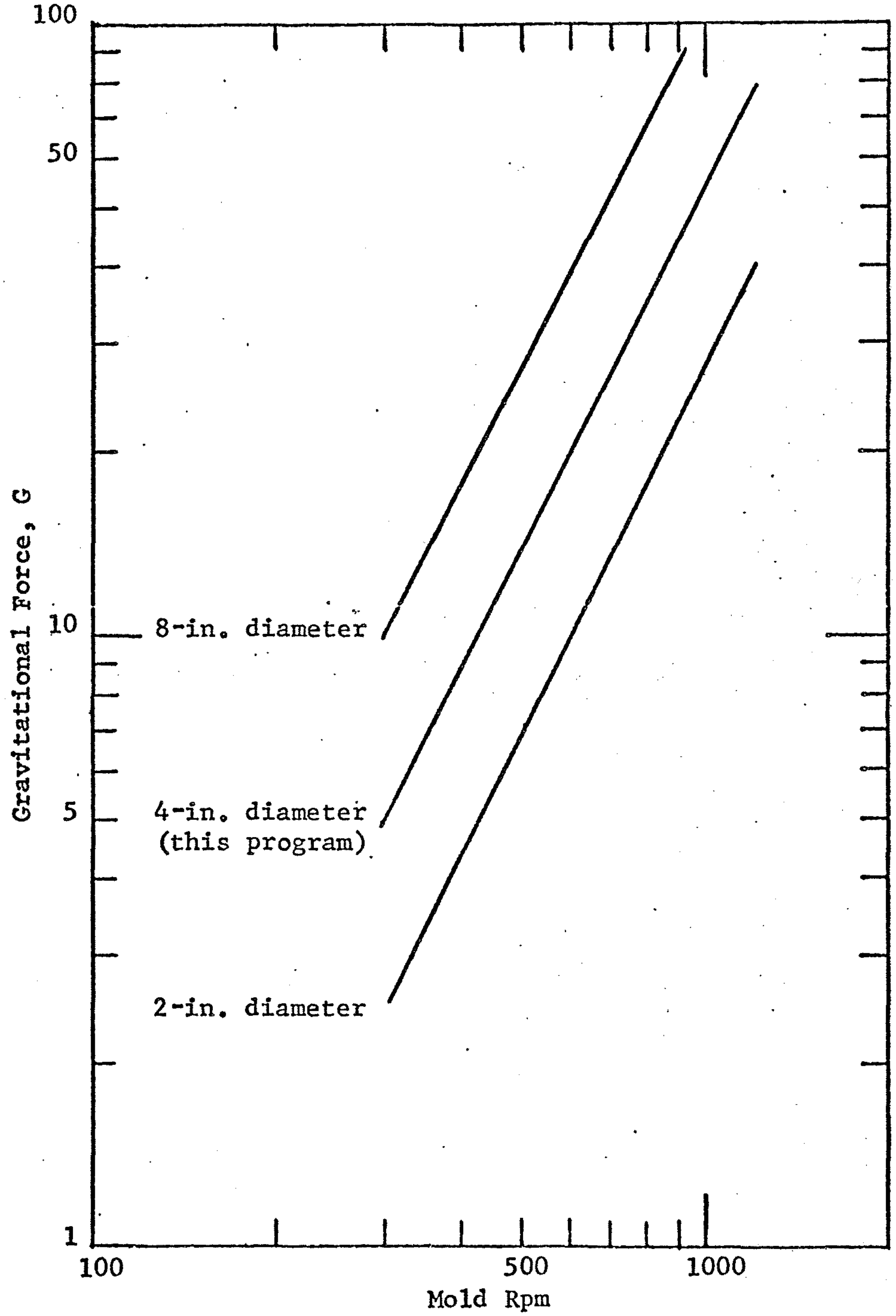

FIGURE 2. GRAVITATIONAL FORCE VERSUS MOLD RPM FOR PIPE SPECIMENS OF VARIOUS DIAMETERS

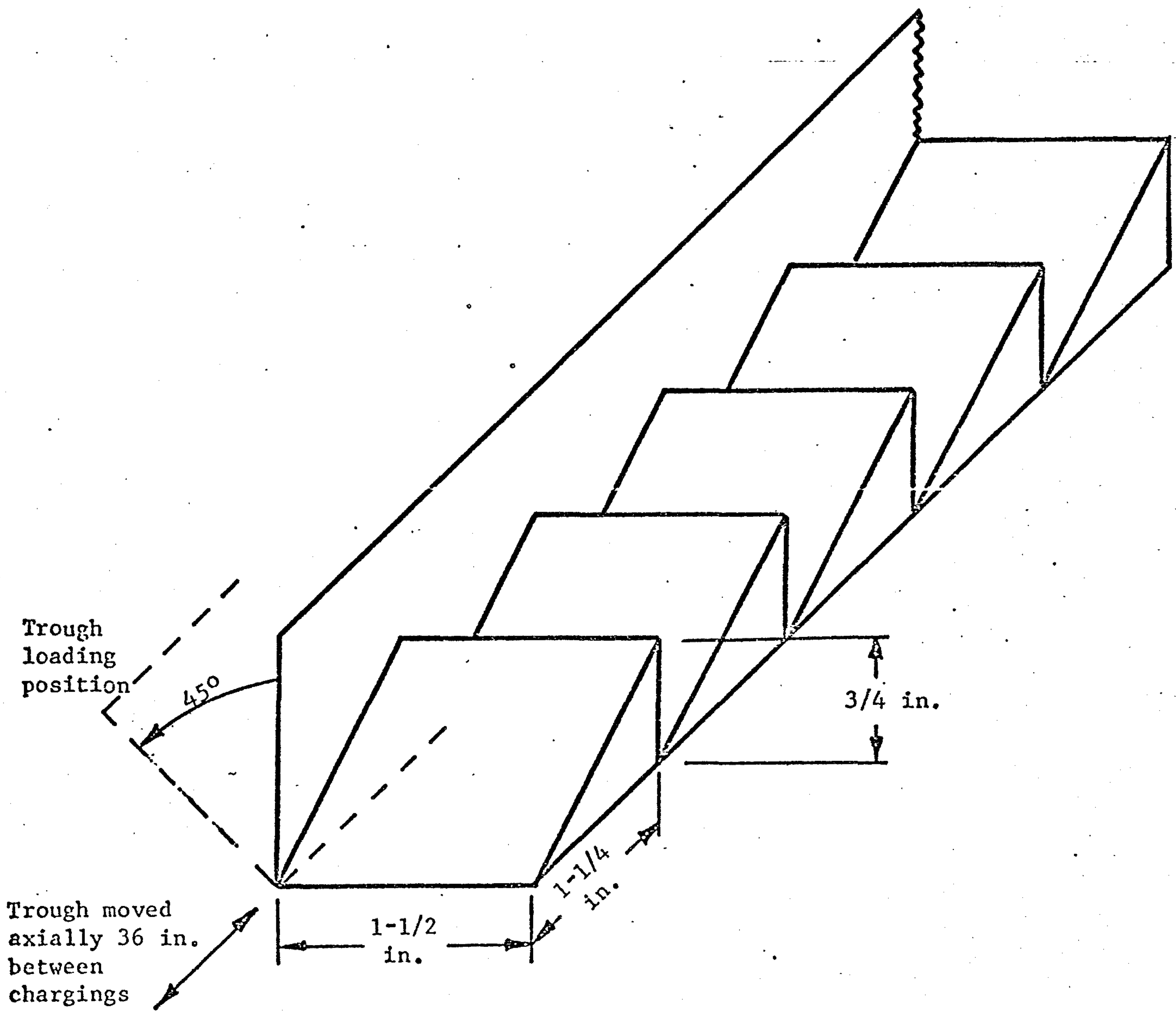

FIGURE 3. SCHEMATIC VIEW OF COMPARTMENTALIZED FEED TROUGH USED TO ORIENT FIBERS IN CIRCUMFERENTIAL DIRECTION

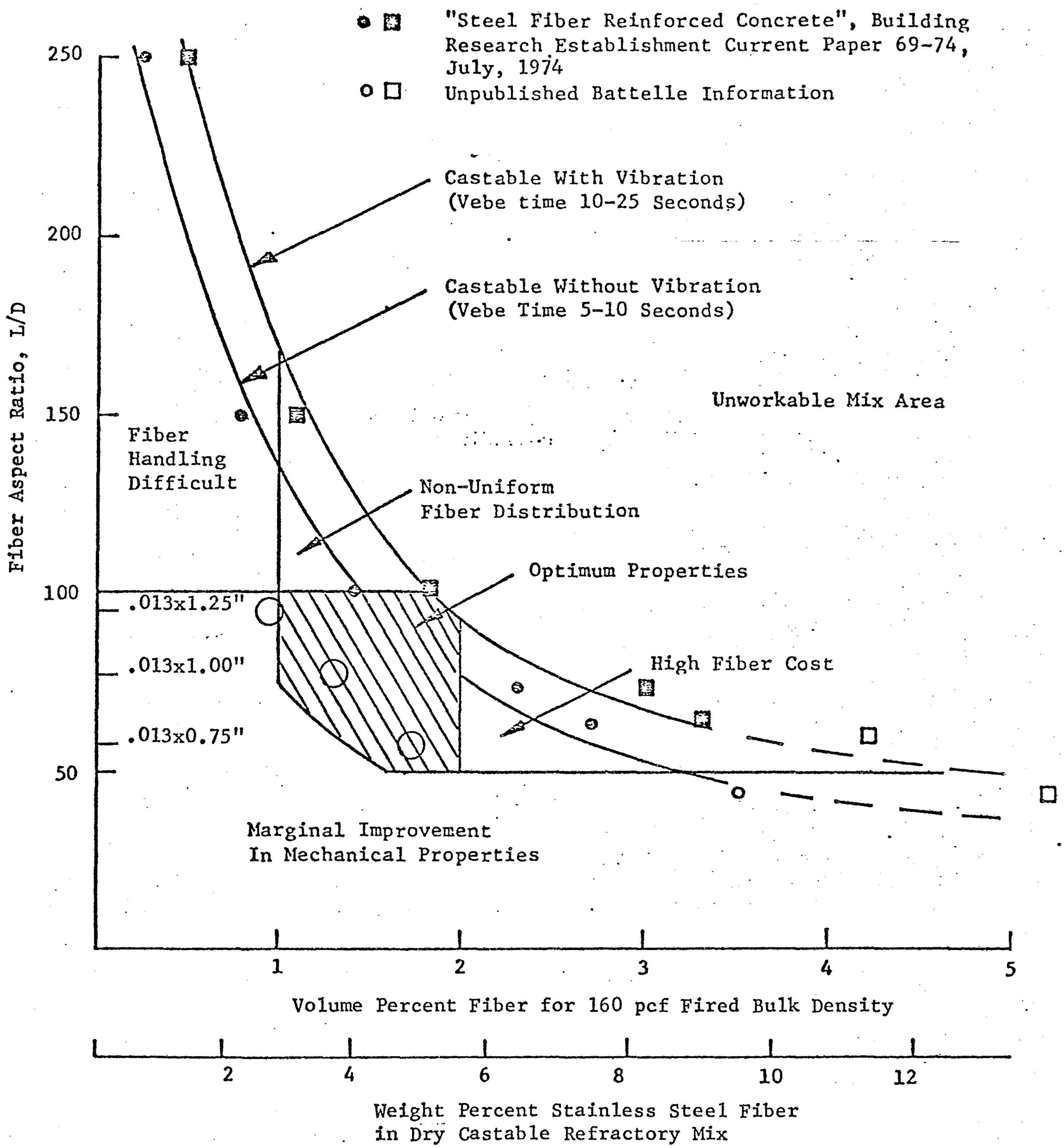

FIGURE 4. MIX WORKABILITY AND TECHNICAL PROPERTY CONSIDERATIONS AS AFFECTED BY FIBER ASPECT RATIO AND VOLUME LOADING IN MOTAR MIXES WITH WATER/CEMENT RATIOS NEAR 0.45

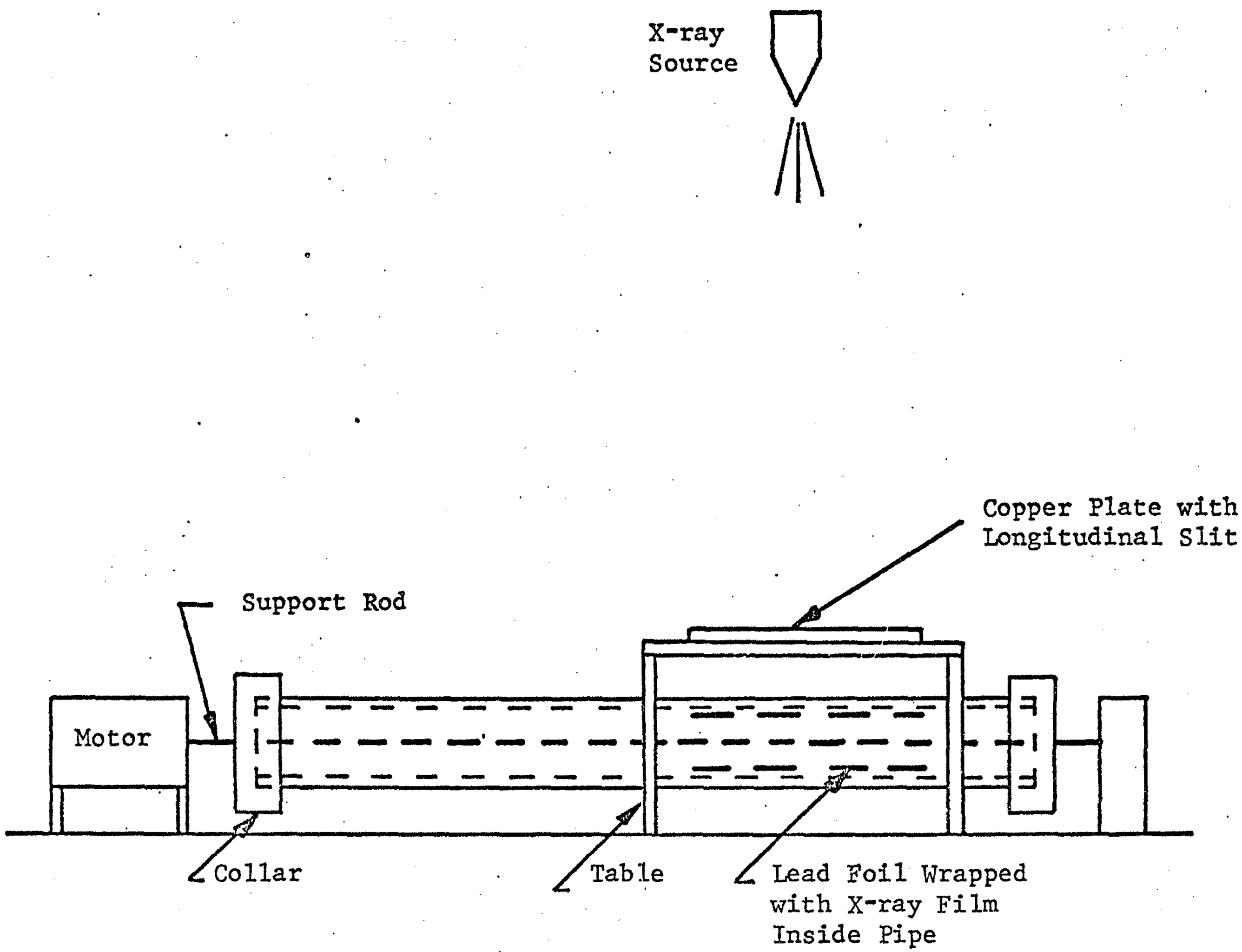

FIGURE 5. SCHEMATIC OF ROTATIONAL ASSEMBLY USED TO X-RAY WALLS OF PIPE SPECIMENS

FIGURE 6. PRINT FROM AN X-RADIOGRAPH OF PIPE NO. 23 SHOWING NONUNIFORM FIBER DISTRIBUTION OBTAINED FROM VIBRATORY CASTING

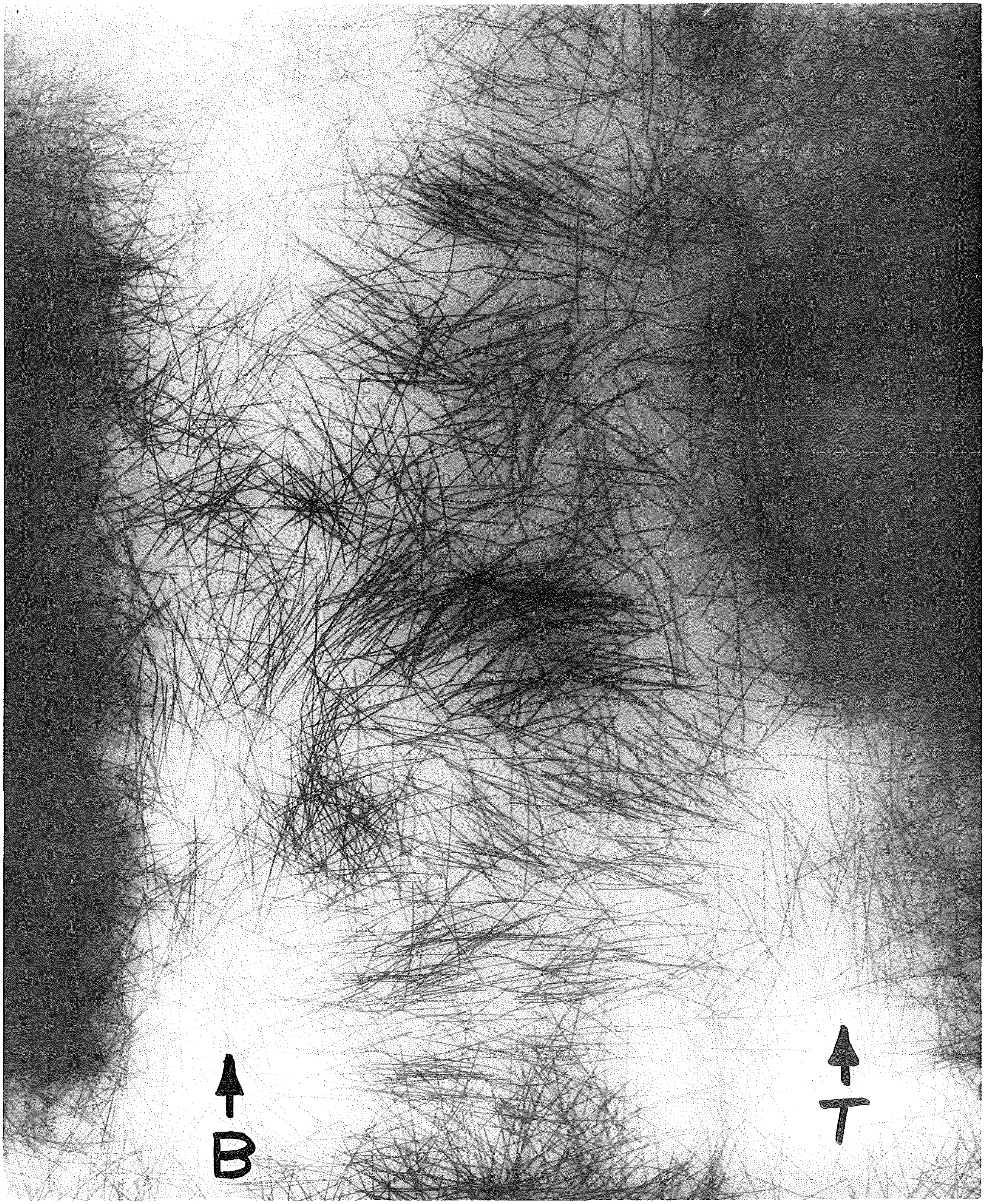

FIGURE 7. PRINT FROM AN X-RADIOGRAPH OF PIPE NO. 24 SHOWING FIBER DISTRIBUTION OBTAINED FROM CHARGING MIX INTO STATIONARY MOLD

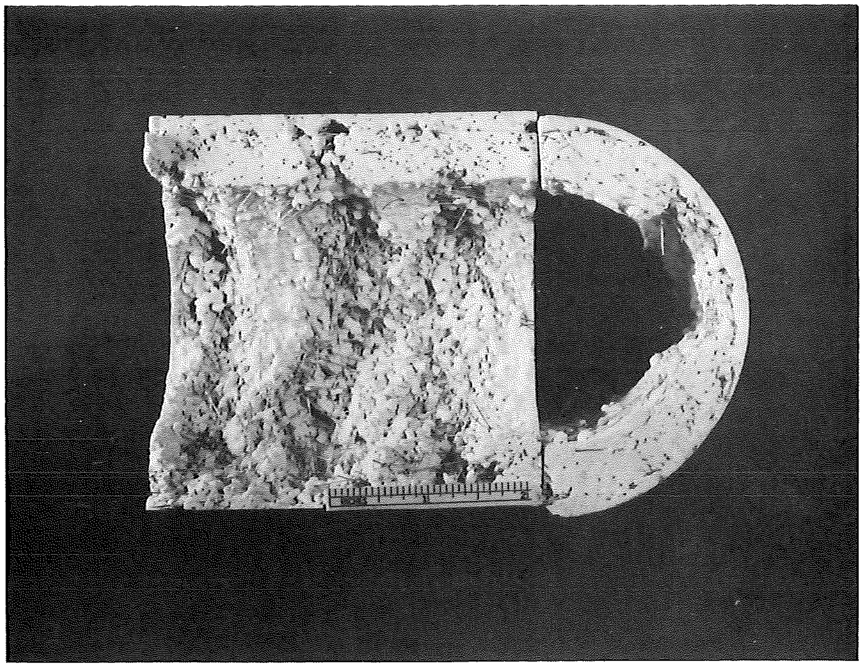

FIGURE 8. PHOTOGRAPH OF POOR-QUALITY PIPE NO. 39 MADE WITH COMPARTMENTALIZED FEED TROUGH

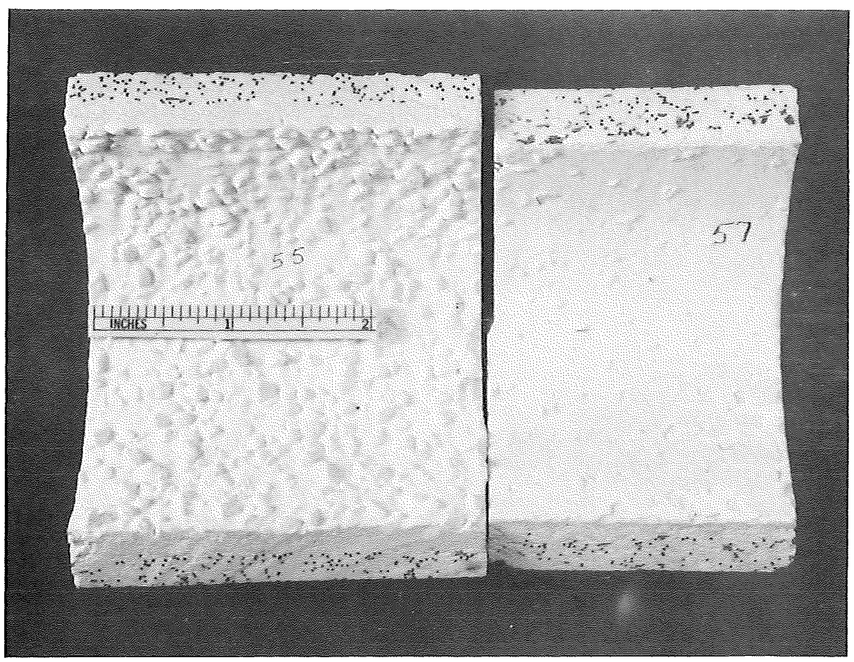

FIGURE 9. PHOTOGRAPH OF PIPE NOS. 55 AND 57 SHOWING FIBER DISTRIBUTION ACROSS PIPE WALL AND DIFFERENT INSIDE-WALL TEXTURES

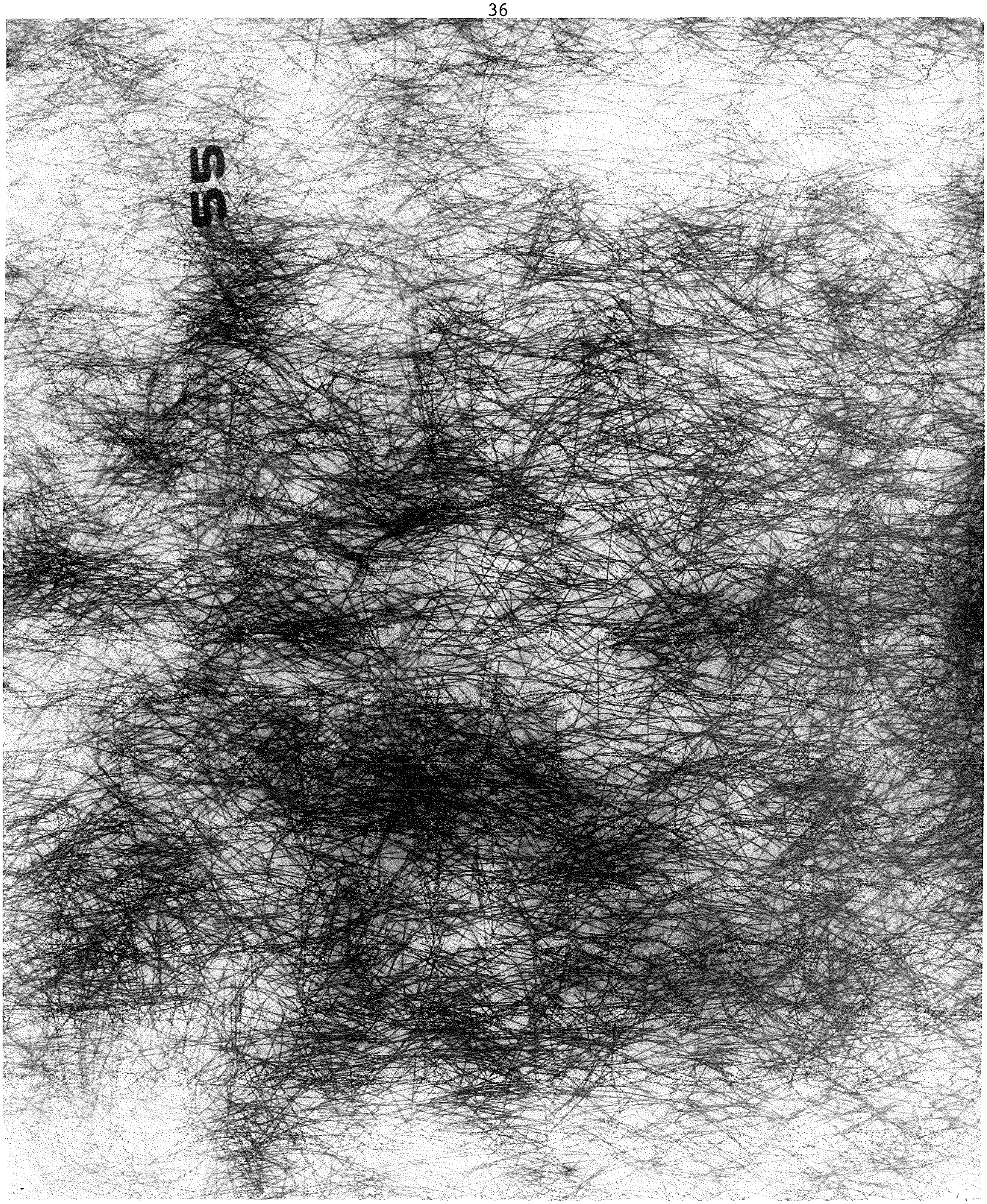

FIGURE 10. PRINT FROM AN X-RADIOGRAPH OF PIPE NO. 55 SHOWING UNIFORM FIBER DISTRIBUTION OBTAINED FROM CHARGING PREBLENDED MIX INTO SPINNING MOLD FROM PLAIN FEED TROUGH

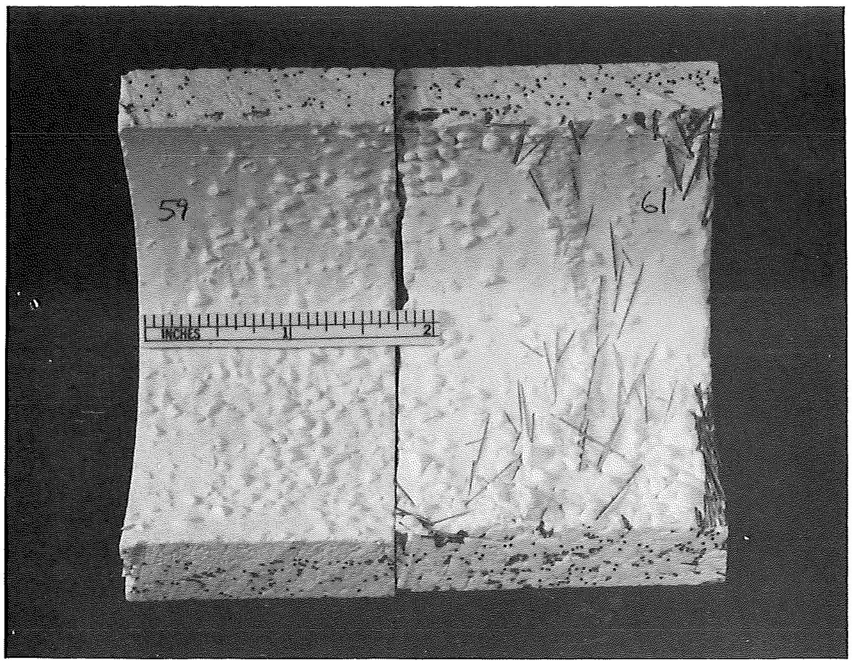

FIGURE 11. PHOTOGRAPH OF PIPE SPECIMEN NO. 59 MADE BY CASTING PREBLENDED MIX, AND SPECIMEN NO. 61 MADE BY CASTING FIBERS SEPARATELY WITH COMPARTMENTALIZED FEED TROUGH

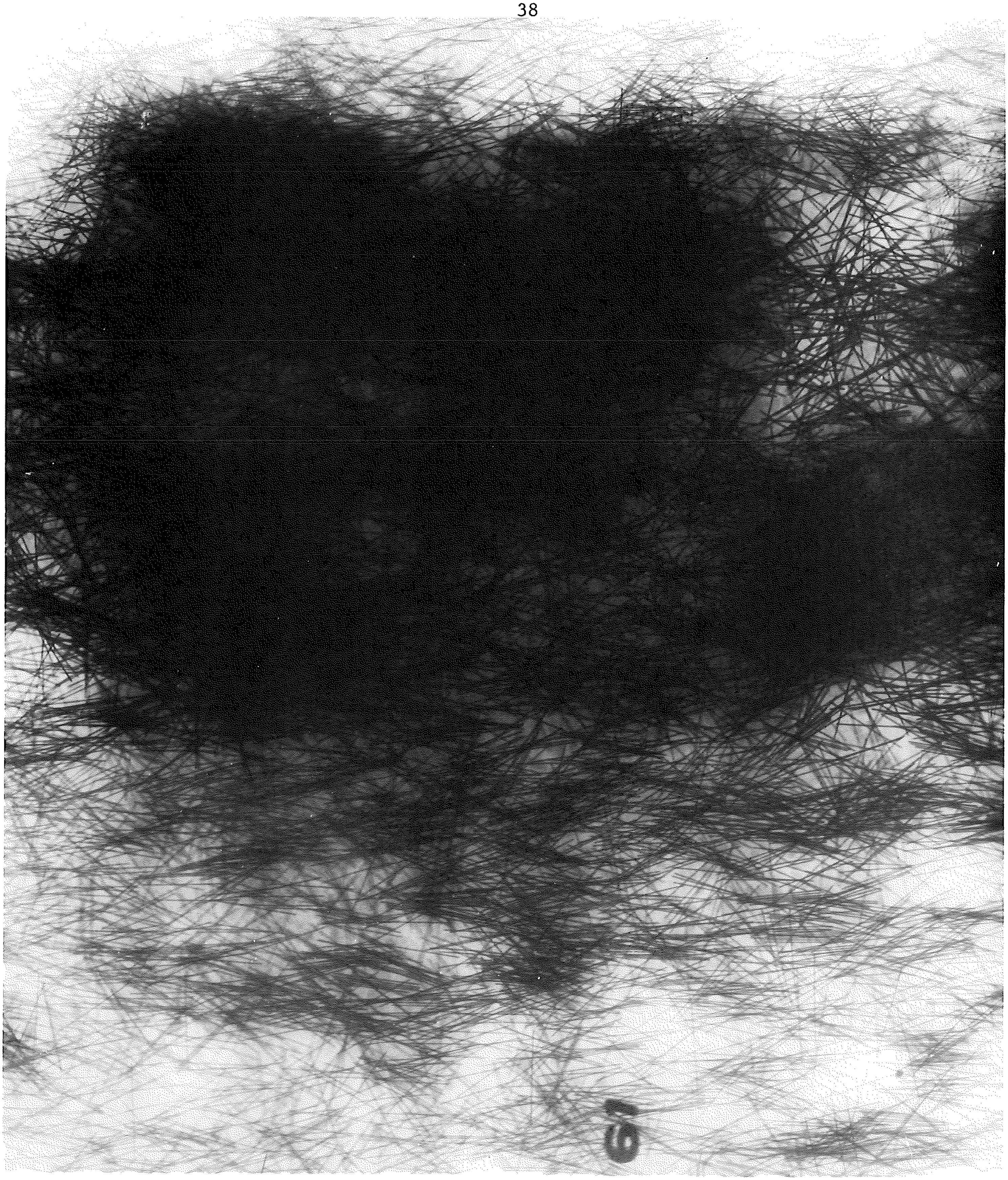

FIGURE 12. PRINT FROM AN X-RADIOGRAPH OF PIPE NO. 61 SHOWING CIRCUMFERENTIAL FIBER ALIGNMENT OBTAINED BY INTRODUCING FIBERS SEPARATELY WITH COMPARTMENTALIZED FEED TROUGH

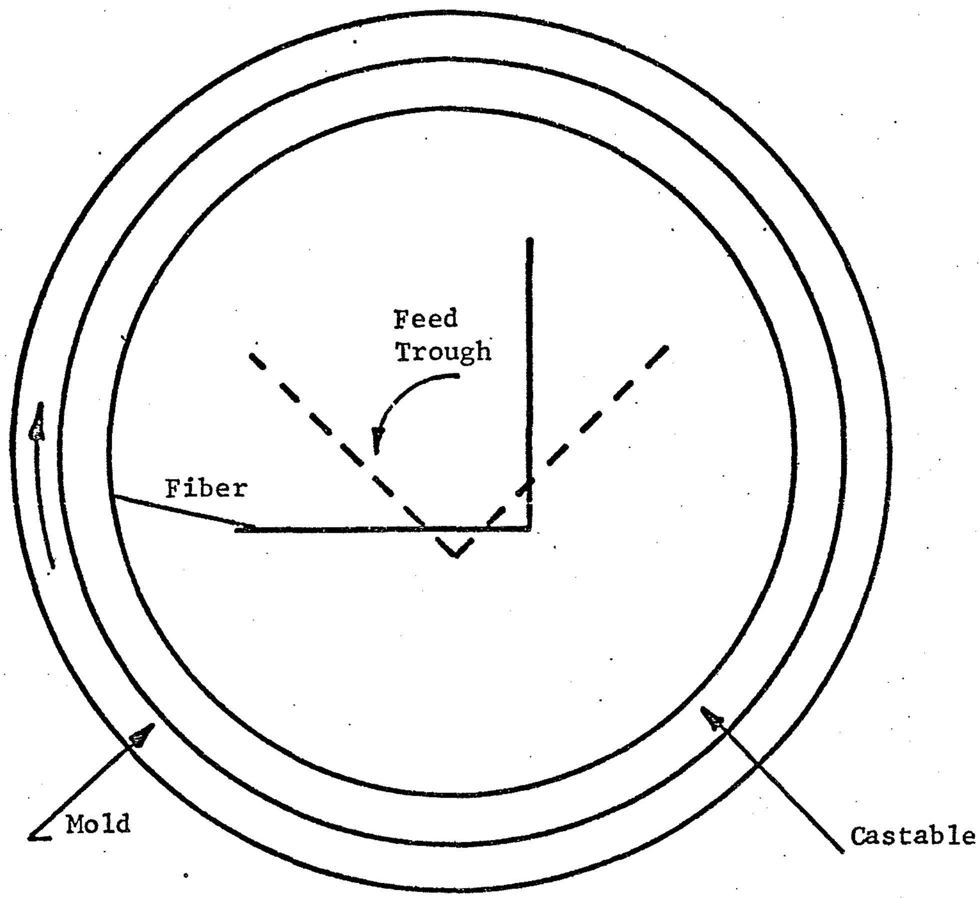

FIGURE 13. SCHEMATIC DIAGRAM OF PREFERENTIAL-FIBER ALIGNMENT OBTAINED BY FEEDING FIBERS AND CASTABLE SEPARATELY

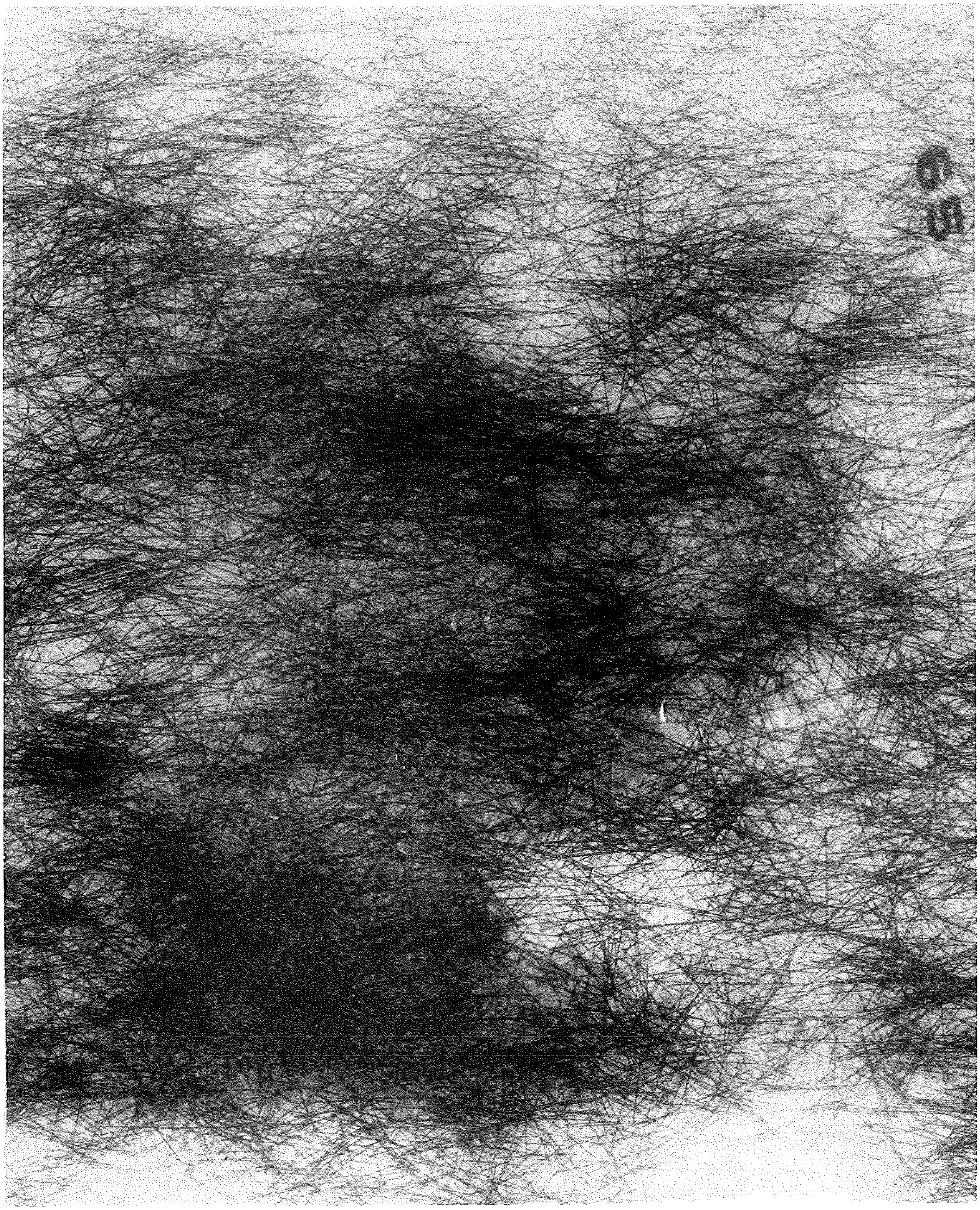

FIGURE 14. PRINT FROM AN X-RADIOGRAPH OF PIPE NO. 65 SHOWING CIRCUMFERENTIAL FIBER ALIGNMENT OBTAINED BY INTRODUCING FIBERS SEPARATELY WITH PLAIN FEED TROUGH